Why building a muon collider

Andrea Wulzer

ICREA @ IFAE

Institut de Física d'Altes Energies

On behalf of

International MUON Collider Collaboration

Why building a muon collider

Andrea Wulzer

ICREA @ IFAE

Institut de Física d'Altes Energies

On behalf of

International MUON Collider Collaboration

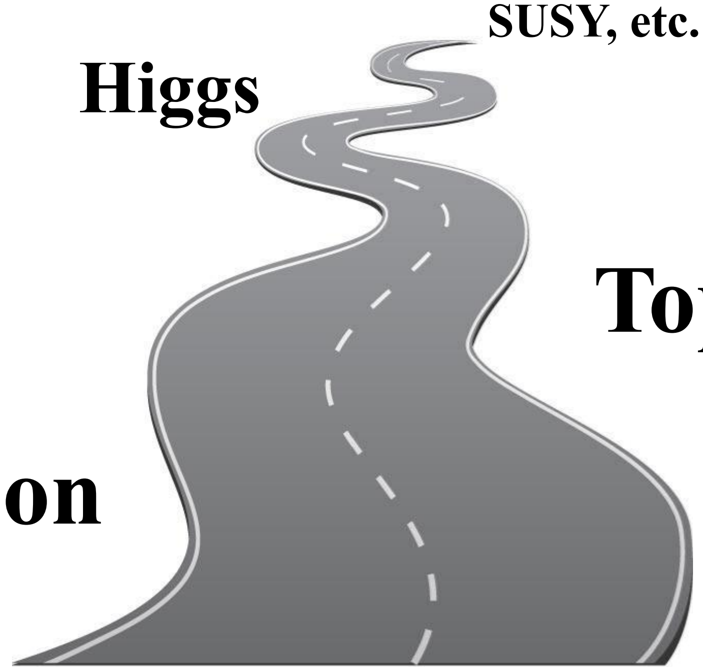
WORK IN PROGRESS

More than a review, what follows is a ToDo list.
For references, and much more, see this EPJC Review:

Towards a Muon Collider

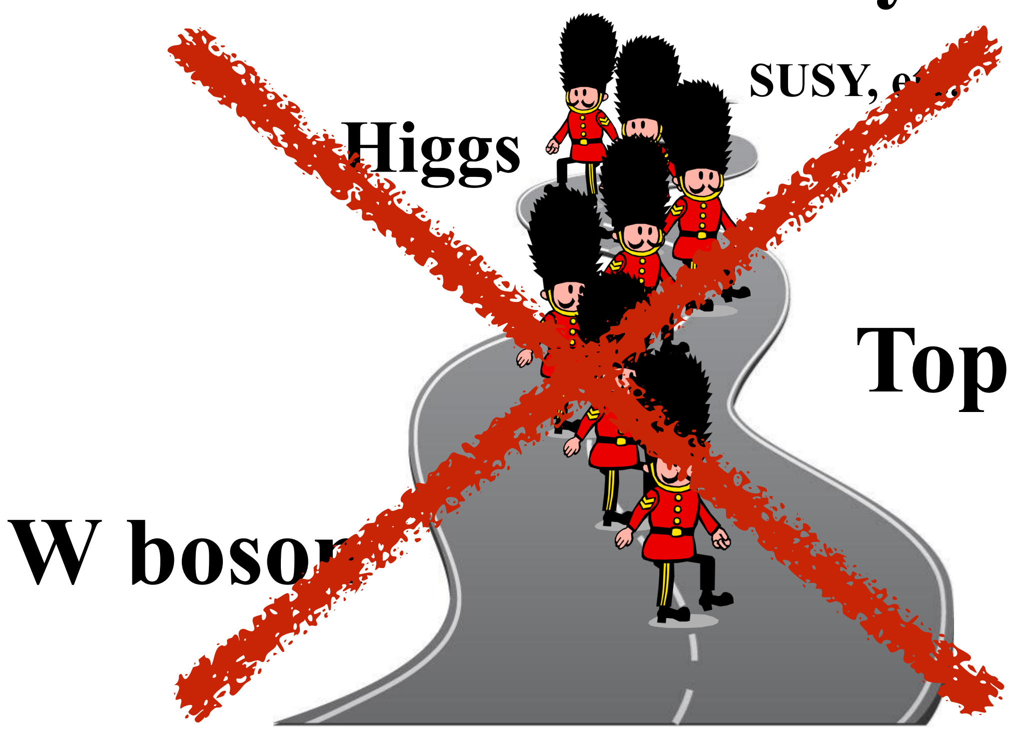
The High Energy Physics Landscape

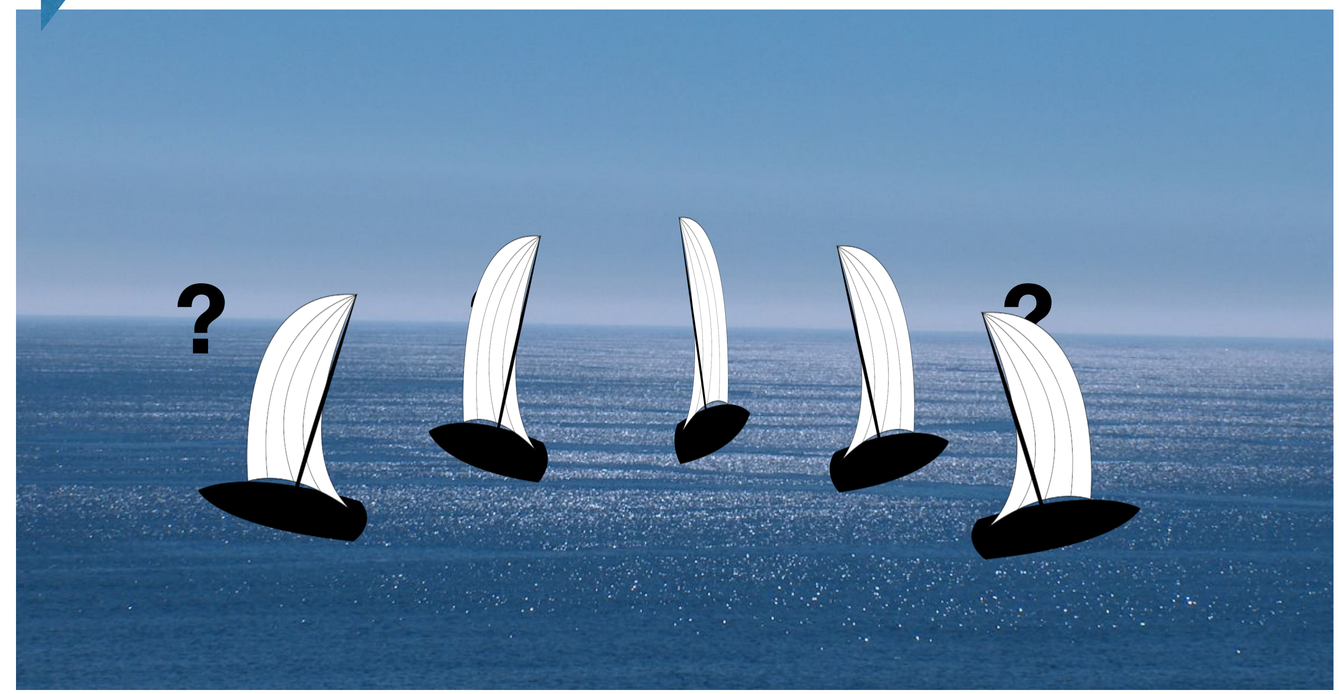
HEP Yesterday **LHC** **HEP Today**



The High Energy Physics Landscape

HEP Yesterday | **LHC** | **HEP Today**





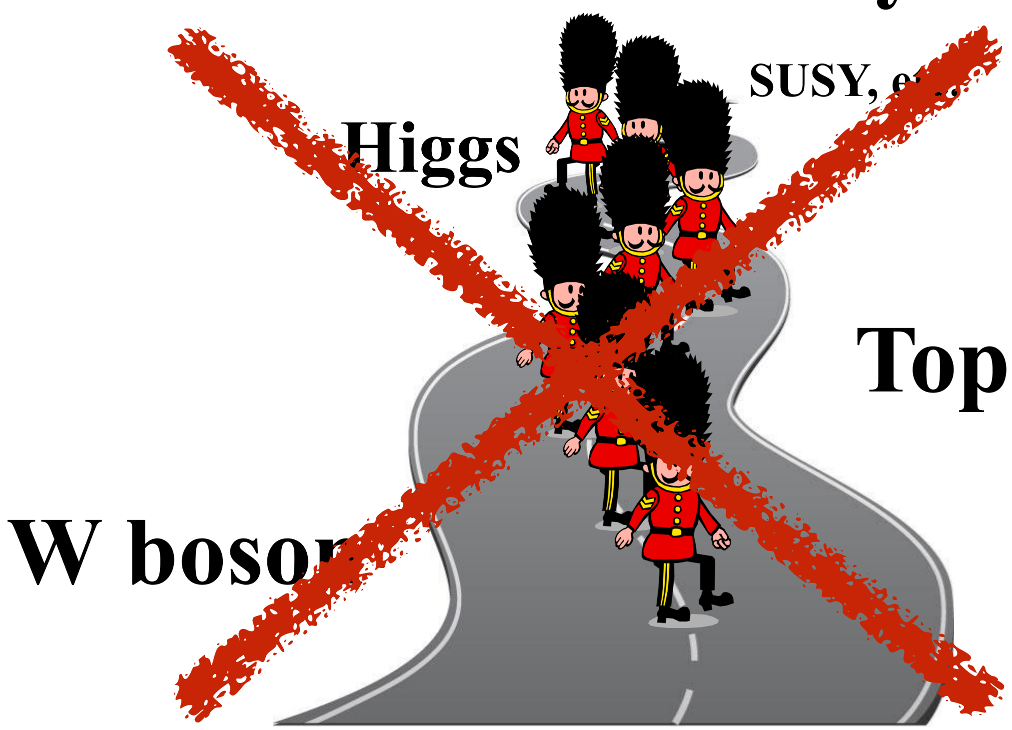
Yesterday, HE-Physicists were used to **follow a road.**

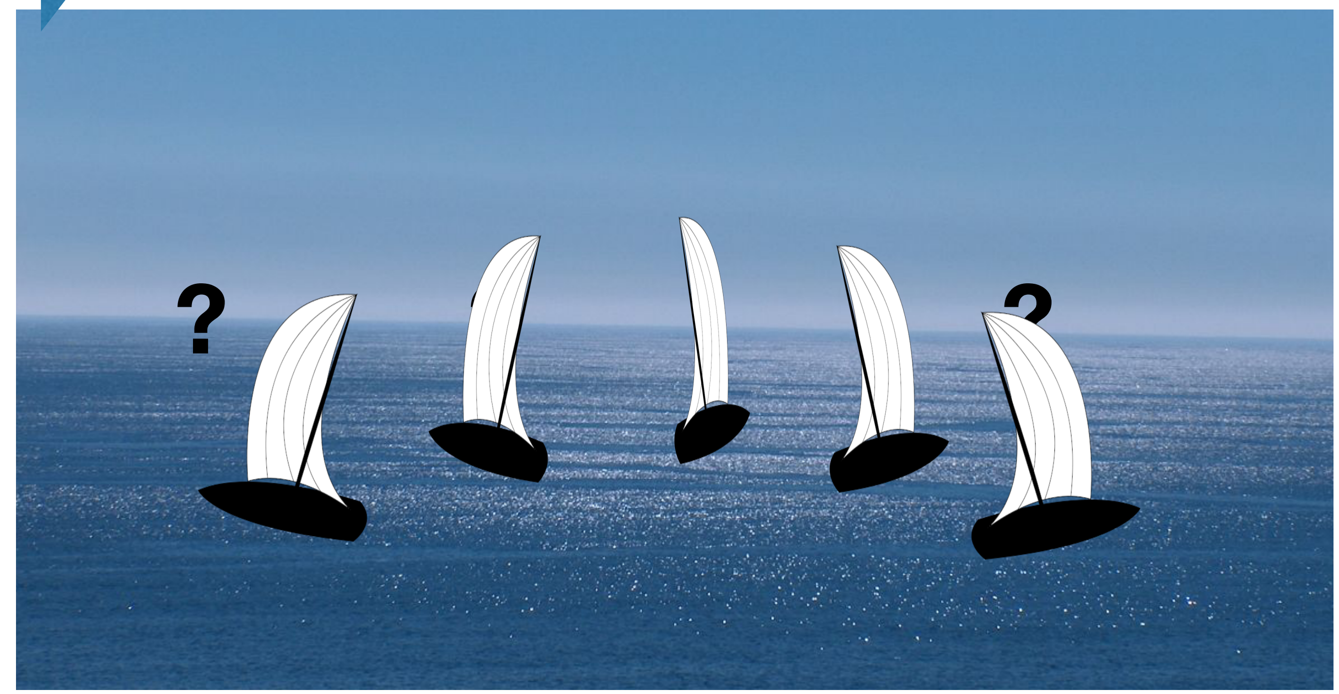
Today, the mission is to **explore uncharted territory***

*Which is **good!**
It means that the next discovery will be more revolutionary than the Higgs one

The High Energy Physics Landscape

HEP Yesterday | **LHC** | **HEP Today**





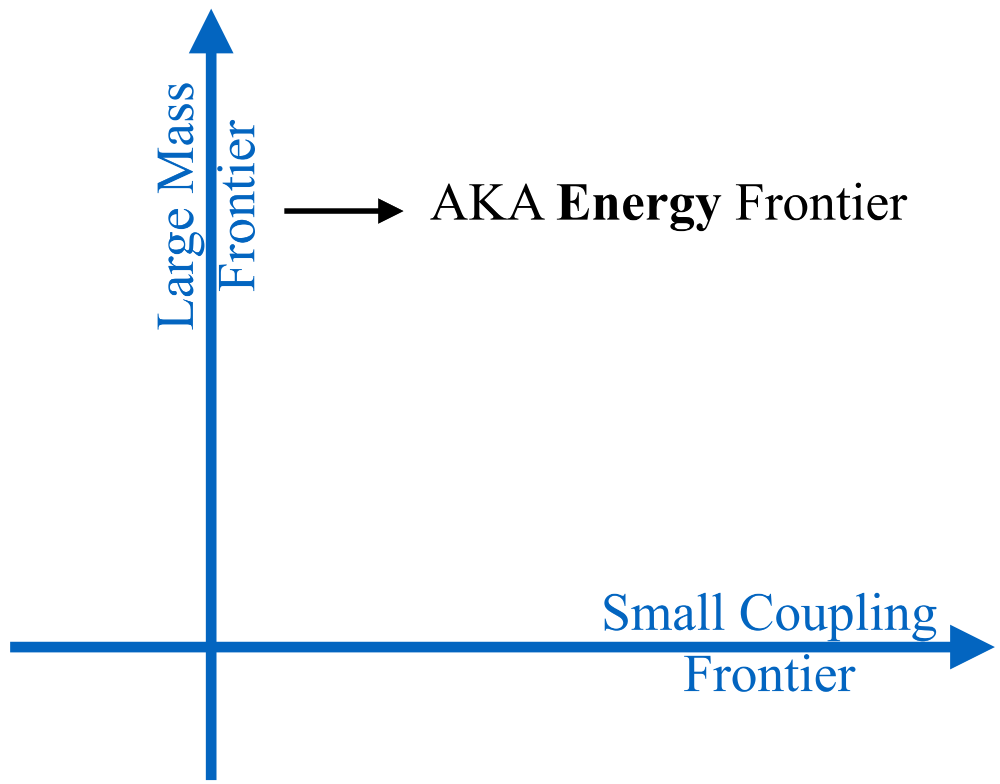
Yesterday, HE-Physicists were used to **follow a road.**

Today, the mission is to **explore uncharted territory***
This is why we started speaking about **Frontiers**

*Which is **good!**
It means that the next discovery will be more revolutionary than the Higgs one

The High Energy Physics Landscape

Our **Frontiers are the directions** in which (i.e., reasons why) New Physics might hide



W bos

Today, the mission is to **explore uncharted territory***
This is why we started speaking about **Frontiers**

*Which is **good!**
It means that the next discovery will be more revolutionary than the Higgs one

Why Colliders?

No single experiment can explore all directions at once.

None (in heaven or earth) can **guarantee discoveries** of new fundamental laws of nature.

Why Colliders?

No single experiment can explore all directions at once.

None (in heaven or earth) can **guarantee discoveries** of new fundamental laws of nature.

But, high energy colliders have **guaranteed outcome:**

Accurate measurements of great variety of observables.

Under precisely known experimental conditions.

+

Accurate predictions within the Standard Model of Particle Physics.

Directly based on microscopic physics laws, principles and techniques.

Why Colliders?

No single experiment can explore all directions at once.

None (in heaven or earth) can **guarantee discoveries** of new fundamental laws of nature.

But, high energy colliders have **guaranteed outcome:**

Accurate measurements of great variety of observables.

Under precisely known experimental conditions.

+

Accurate predictions within the Standard Model of Particle Physics.

Directly based on microscopic physics laws, principles and techniques.

=

1) Complete and conclusive **exploration** of the Energy Frontier

2) Sharp answers to well-posed **Beyond the SM questions**

Why Colliders?

No single experiment can explore all directions at once.

None (in heaven or earth) can **guarantee discoveries** of new fundamental laws of nature.

But, high energy colliders have **guaranteed outcome:**

Accurate measurements of great variety of observables.

Under precisely known experimental conditions.

+

Accurate predictions within the Standard Model of Particle Physics.

Directly based on microscopic physics laws, principles and techniques.

=

1) Complete and conclusive **exploration** of the Energy Frontier

2) Sharp answers to well-posed **Beyond the SM questions**

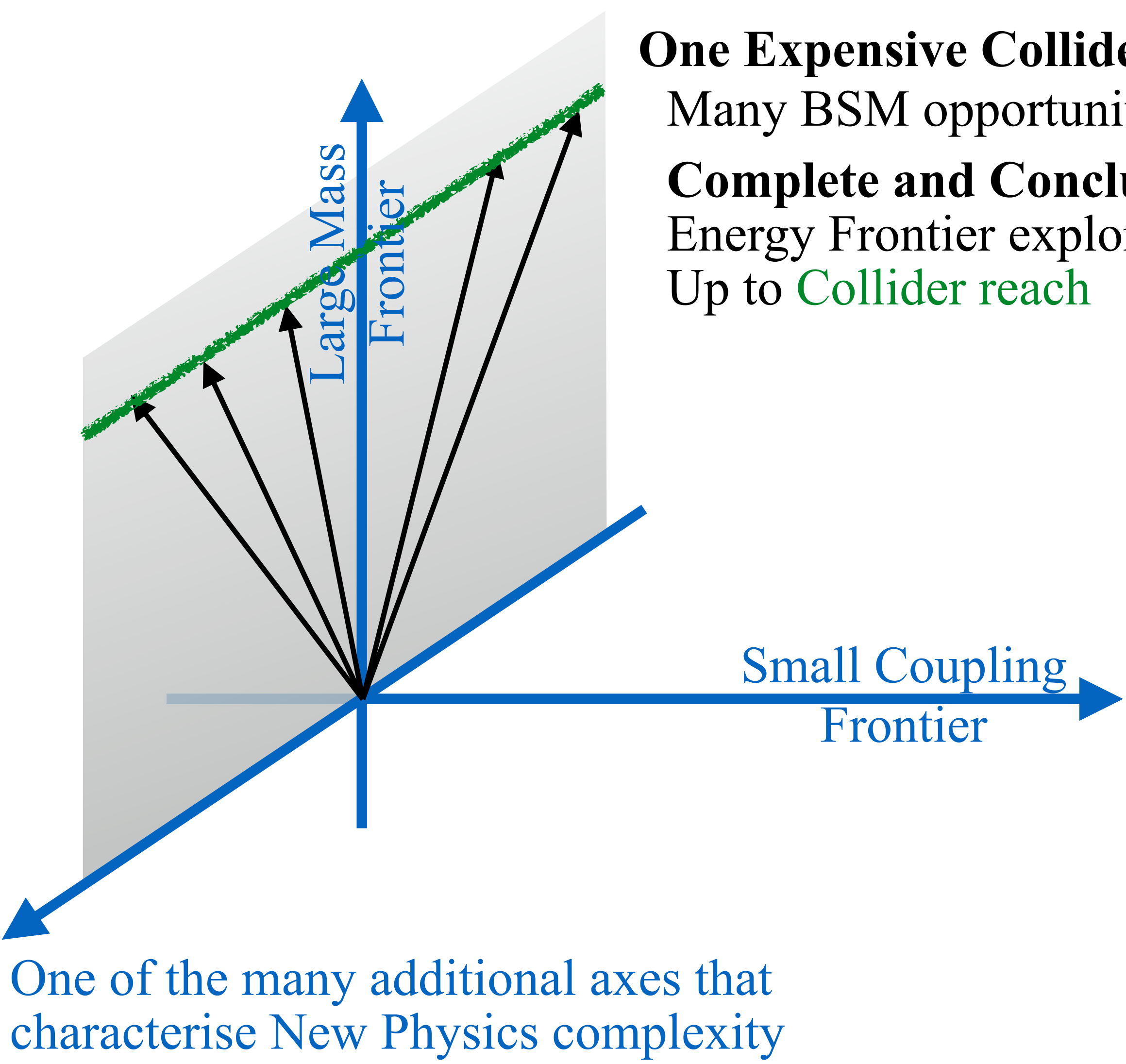
Only one drawback: they are **Expensive**.

Why Colliders?

Expensive? Yes, no doubt, but …

One Expensive Collider
Many BSM opportunities

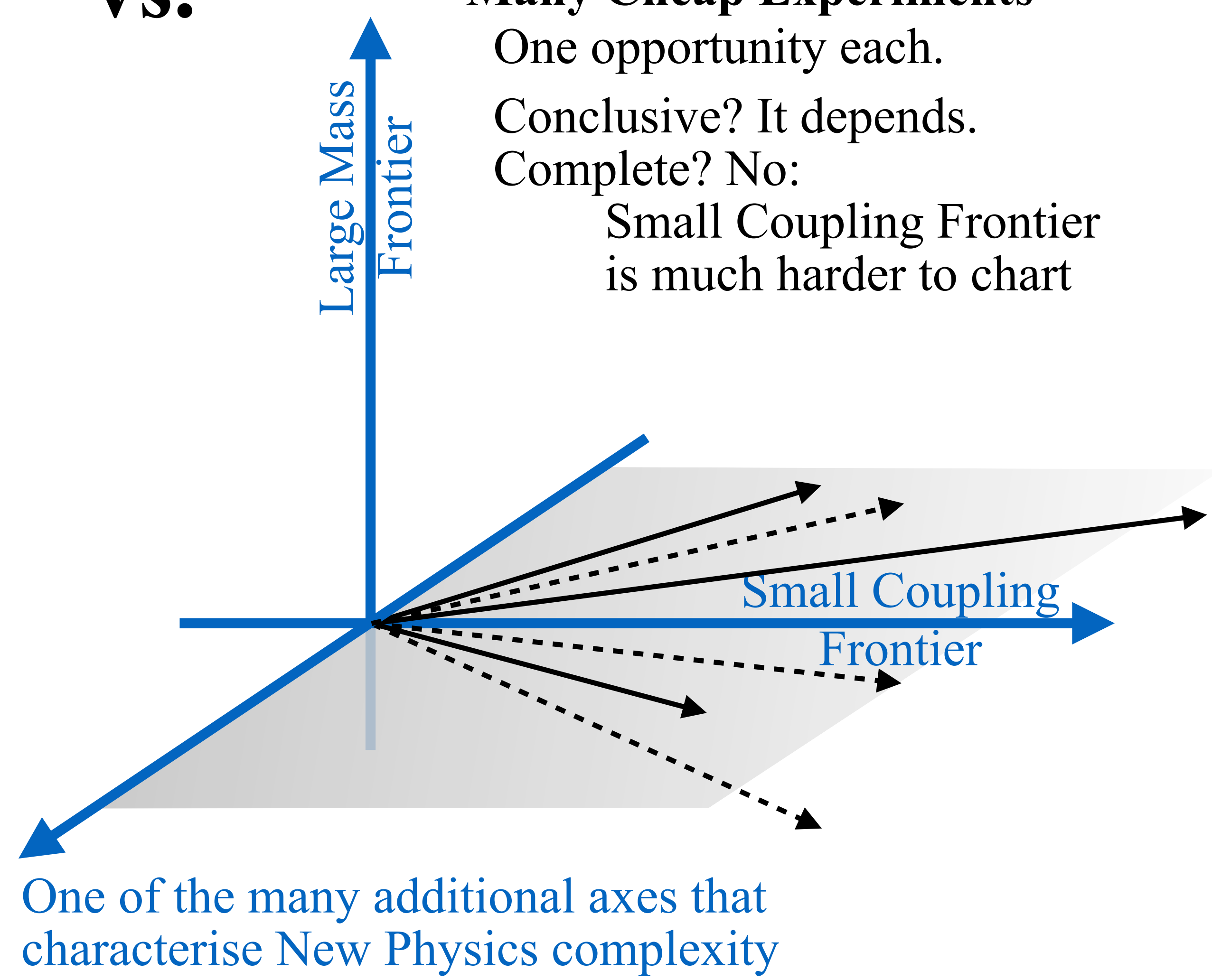
Complete and Conclusive
Energy Frontier exploration.
Up to Collider reach



vs.

Many Cheap Experiments
One opportunity each.

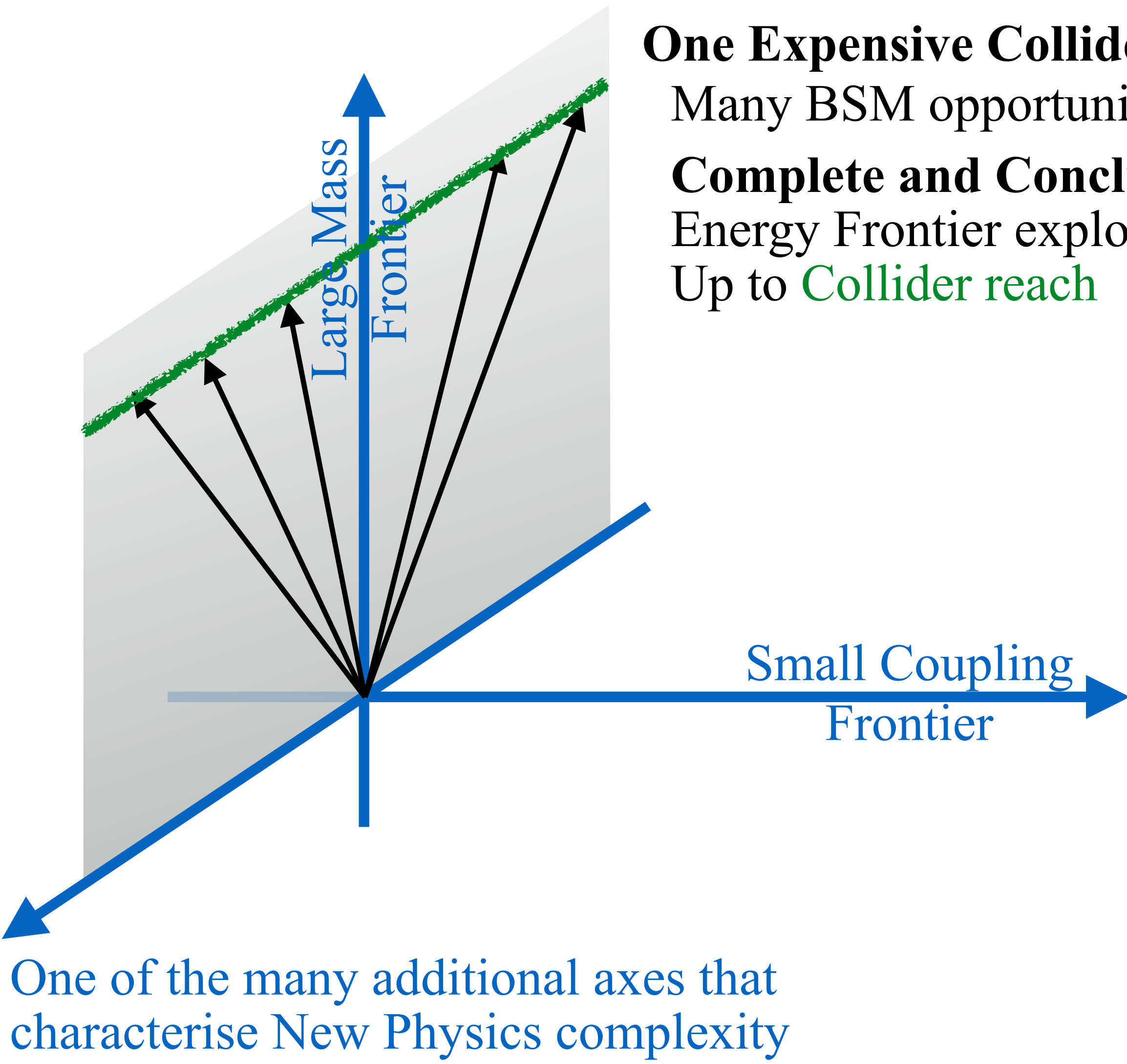
Conclusive? It depends.
Complete? No:
Small Coupling Frontier
is much harder to chart



Why Colliders?

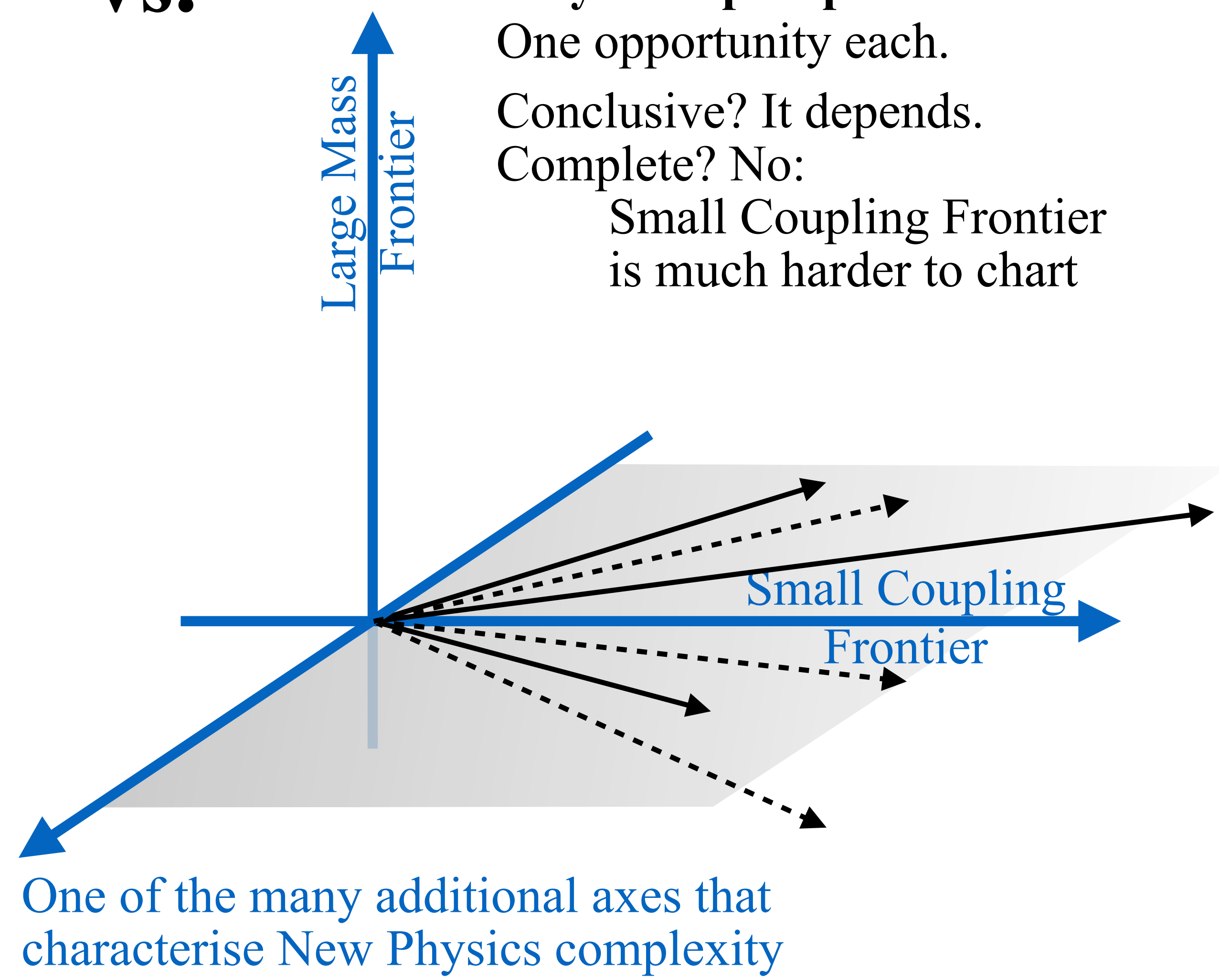
Expensive? Yes, no doubt, but …

One Expensive Collider
Many BSM opportunities
Complete and Conclusive
Energy Frontier exploration.
Up to Collider reach



vs.

Many Cheap Experiments
One opportunity each.
Conclusive? It depends.
Complete? No:
Small Coupling Frontier
is much harder to chart



Still, no doubt that next big project, to have a chance, must be ambitious enough to make **great jump ahead** in exploration of **multiple directions**
[even better if constructed with **revolutionary technology**]

Why Muons?

Leptons are the ideal probes of short-distance physics:

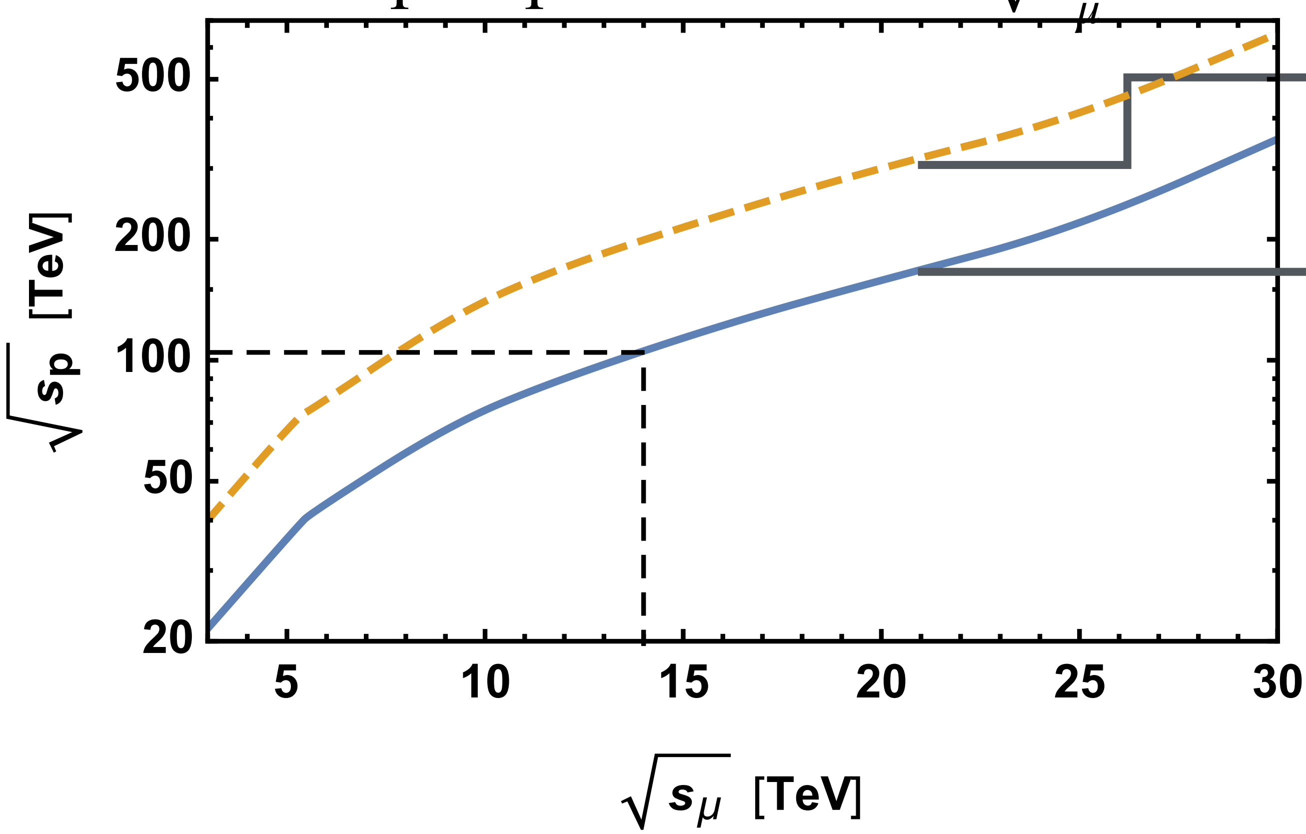
All the energy is stored in the colliding partons
No energy “waste” due to parton distribution functions
High-energy physics probed with much smaller collider energy

Why Muons?

Leptons are the ideal probes of short-distance physics:

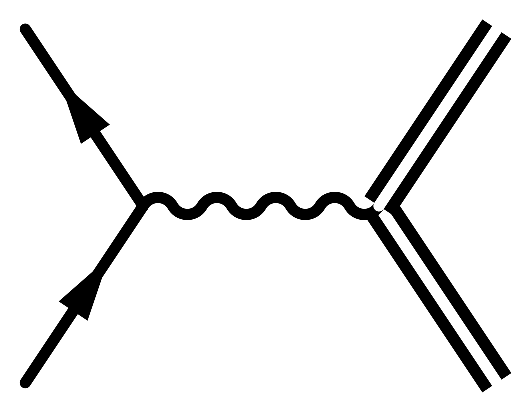
All the energy is stored in the colliding partons
No energy "waste" due to parton distribution functions
High-energy physics probed with much smaller collider energy

pp $\sqrt{s}$ at which $\sigma_{pp} = \sigma_{\mu\mu}$
for pair prod. with $M \sim \sqrt{s_\mu}$



Estimate for EWK-only charged particles

Estimate for EWK&QCD charged particles



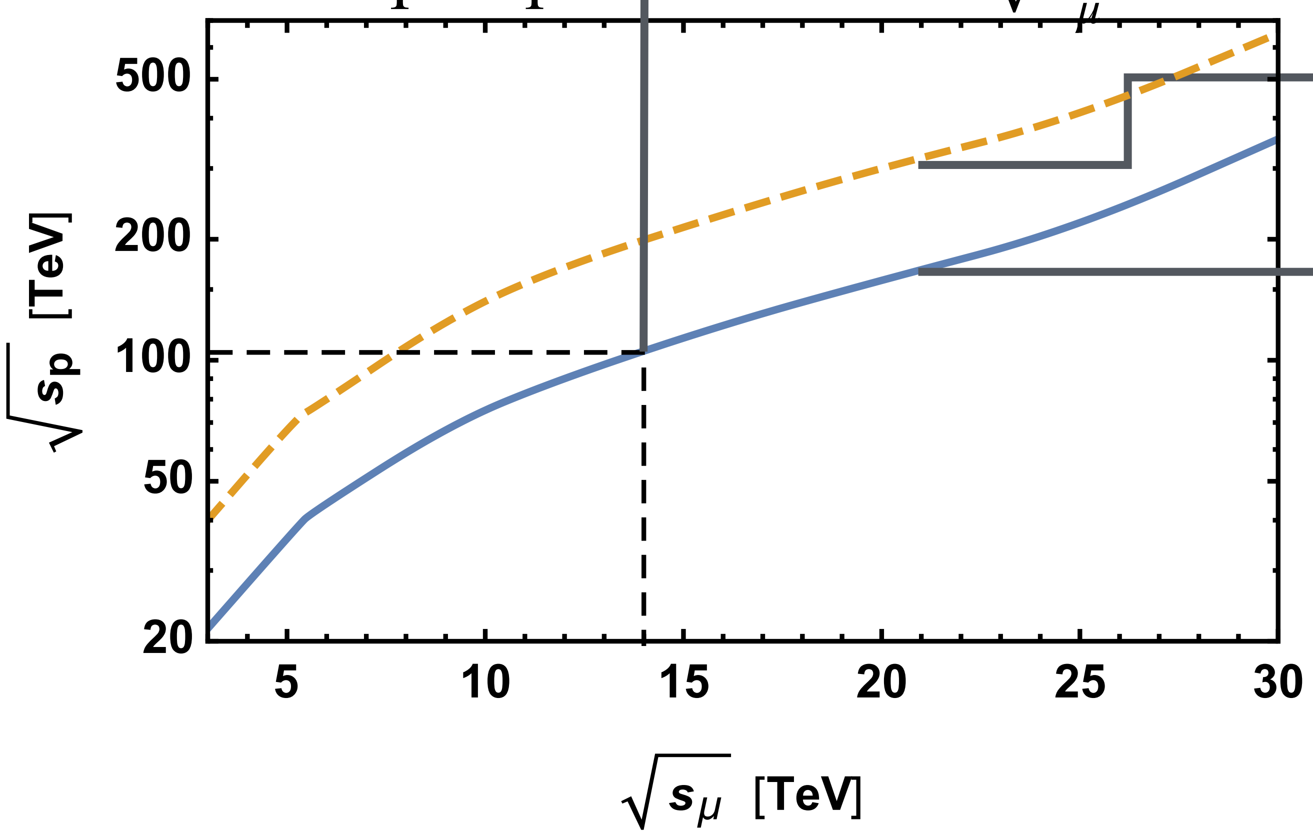
Why Muons?

Leptons are the ideal probes of short-distance physics:

All the energy is stored in the colliding partons
No energy “waste” due to parton distribution functions
High-energy physics probed with much smaller collider energy

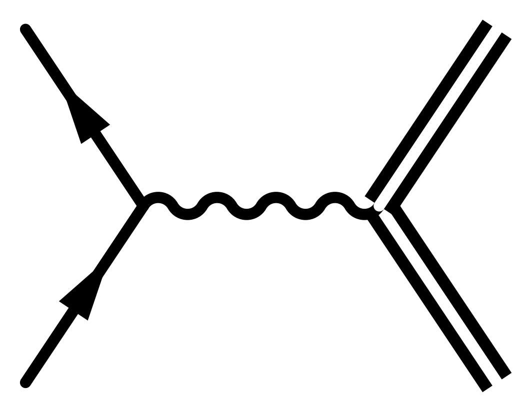
For reference:
14 TeV μ-collider ~ FCC@100 TeV

pp $\sqrt{s}$ at which $\sigma_{pp} = \sigma_{\mu\mu}$
for pair prod. with $M \sim \sqrt{s}_\mu$



Estimate for EWK-only charged particles

Estimate for EWK&QCD charged particles



Why Muons?

Leptons are the ideal probes of short-distance physics:

All the energy is stored in the colliding partons
No energy "waste" due to parton distribution functions
High-energy physics probed with much smaller collider energy

Electrons radiate too much

[cannot accelerate them in rings above few 100 GeV]
[linear colliders limited to few TeV by size and power]

Why Muons?

Leptons are the ideal probes of short-distance physics:

All the energy is stored in the colliding partons
No energy "waste" due to parton distribution functions
High-energy physics probed with much smaller collider energy

Electrons radiate too much

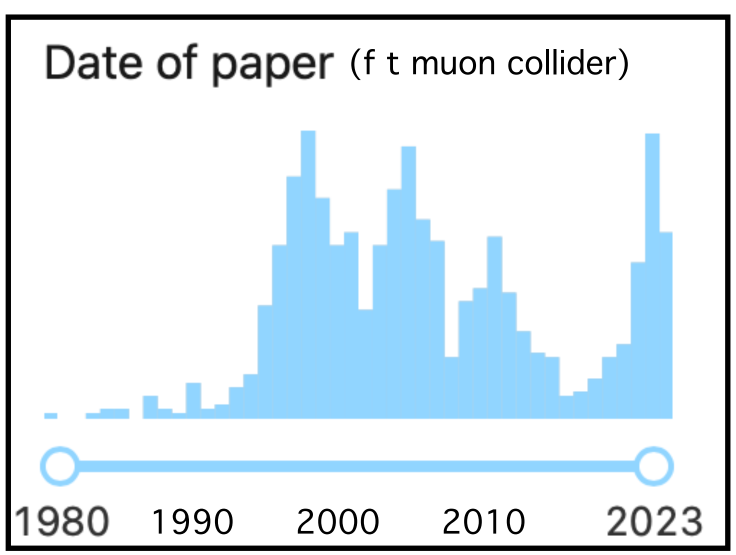
[cannot accelerate them in rings above few 100 GeV]
[linear colliders limited to few TeV by size and power]

Muon Colliders

1980 First ideas

2011-2014 MAP in U.S. Muon Accelerator Program

2020 Update of EU Strategy outcome: set up collaboration



International MUON Collider Collaboration

muoncollider.web.cern.ch

Why Muons?

Leptons are the ideal probes of short-distance physics:

All the energy is stored in the colliding partons
No energy "waste" due to parton distribution functions
High-energy physics probed with much smaller collider energy

Electrons radiate too much

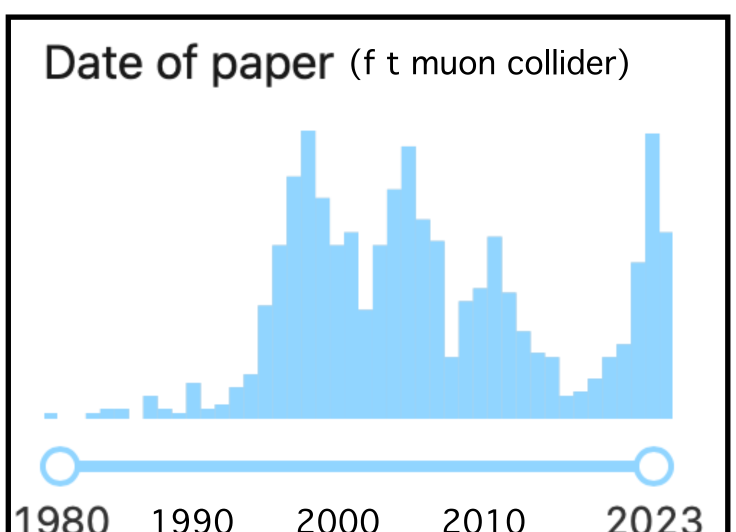
[cannot accelerate them in rings above few 100 GeV]
[linear colliders limited to few TeV by size and power]

Muon Colliders

1980
First ideas

2011-2014 MAP in U.S.
Muon Accelerator Program

2020 Update of EU Strategy
outcome: set up collaboration



Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	$1 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14

5 yrs run, 1 IP: $\mathfrak{L}_{\text{int}} = 10\,\text{ab}^{-1} \left(\frac{E_{\text{cm}}}{10\,\text{TeV}} \right)^2$

Natural quadratic lumi scaling at MuC

International
UON Collider
Collaboration

muoncollider.web.cern.ch

Physics Opportunities

The muon collider combines pp and ee advantages:

- High available energy for new heavy particles production

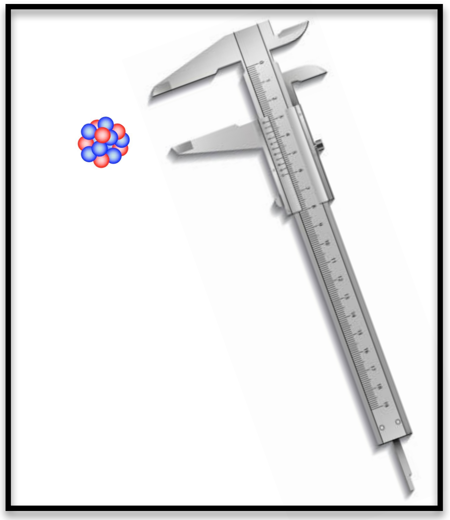
Energy

Physics Opportunities

The muon collider combines pp and ee advantages:

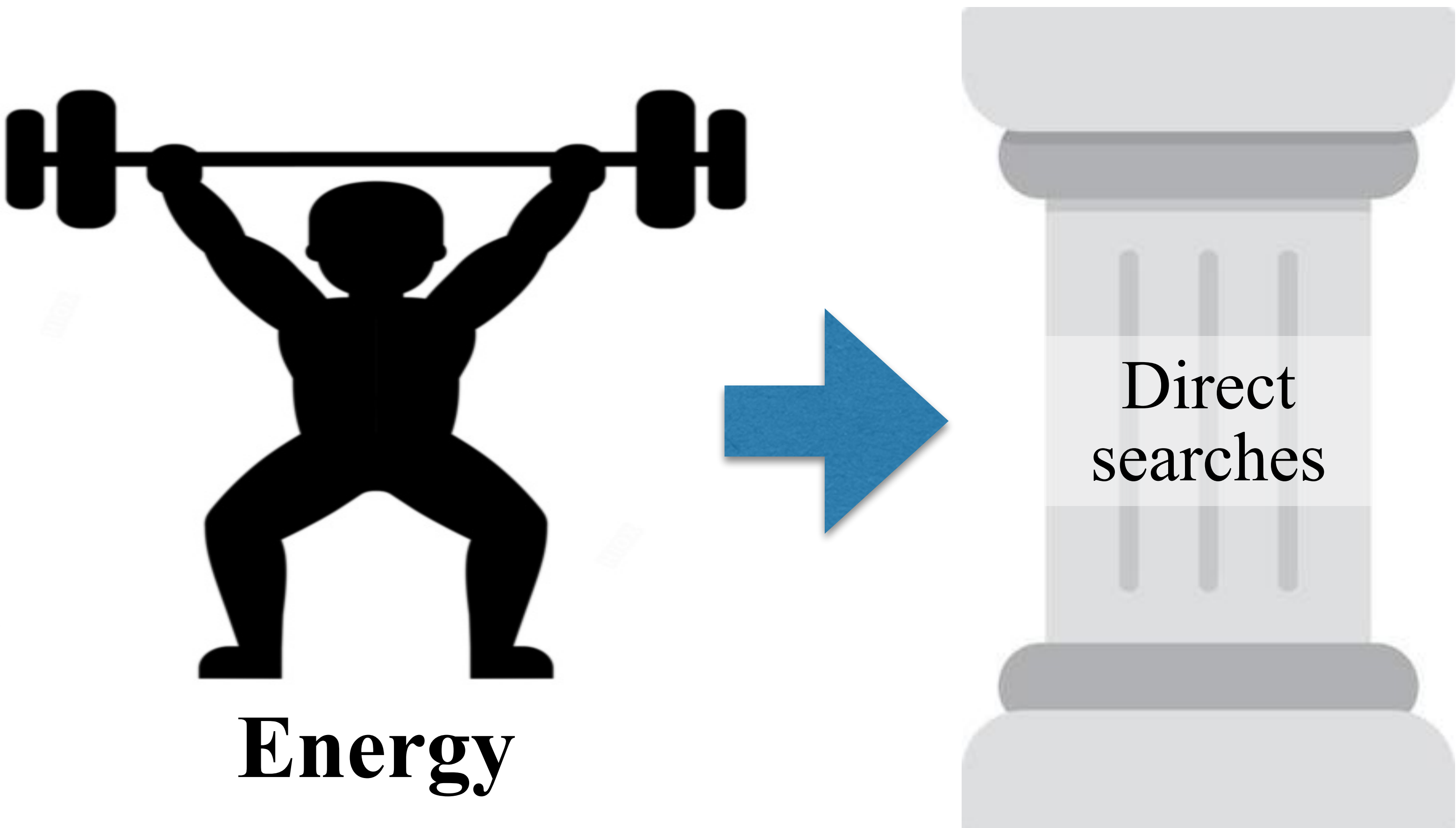
- High available energy for new heavy particles production
- High available statistics for precise measurements (and no QCD bck)

Energy

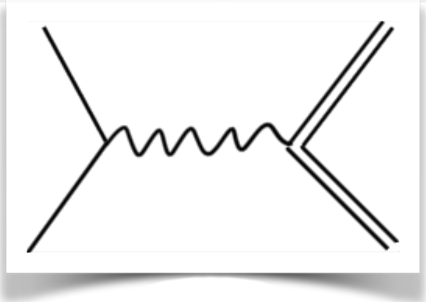


Precision

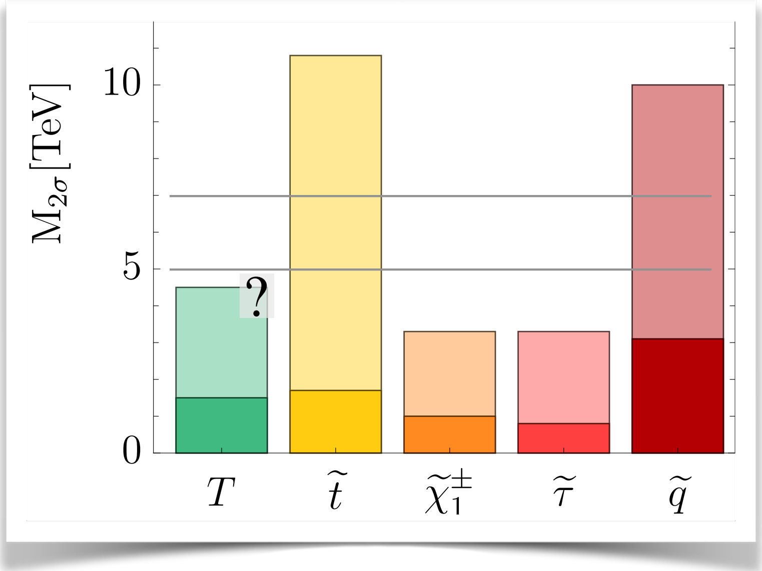
Direct searches



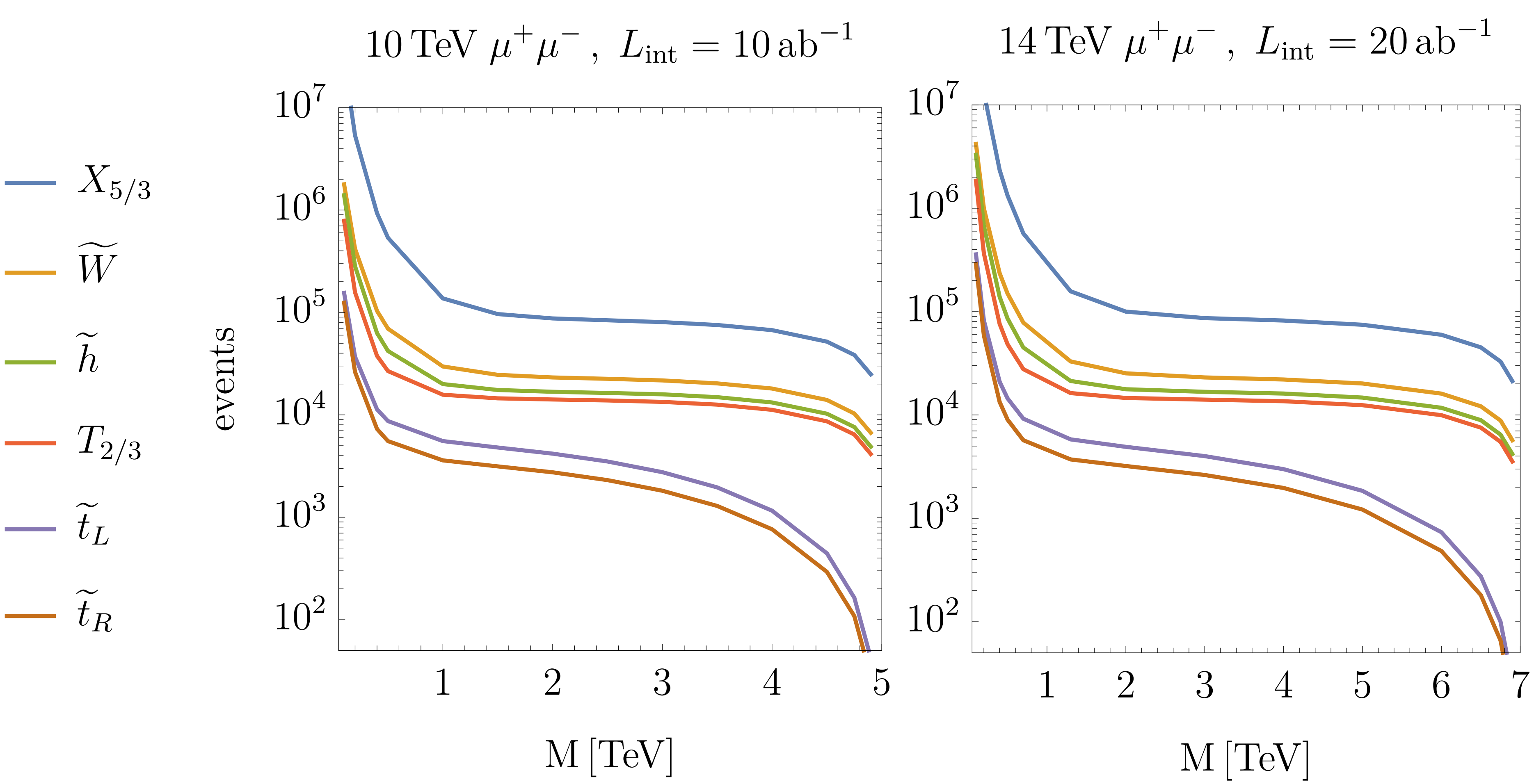
Direct searches



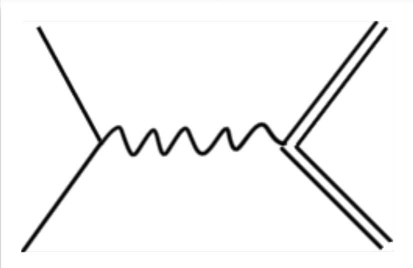
μμ annihilation: copious production of **EW-charged particles** up to $E_{cm}/2$



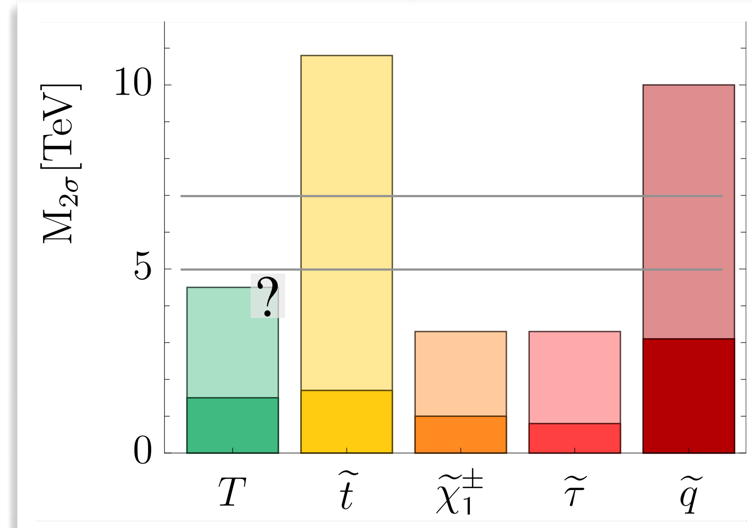
These searches can, for instance, advance probes of (un)-Natural EWSB by one or two orders of magnitude



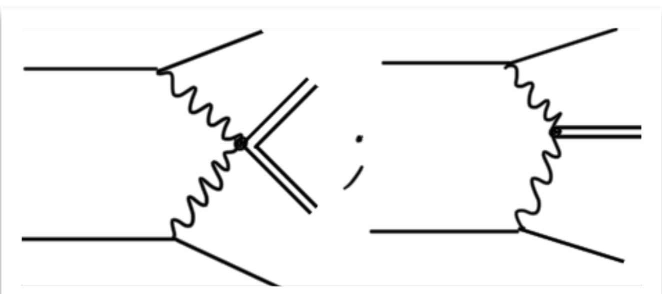
Direct searches



μμ annihilation: copious production of **EW-charged particles** up to $E_{cm}/2$

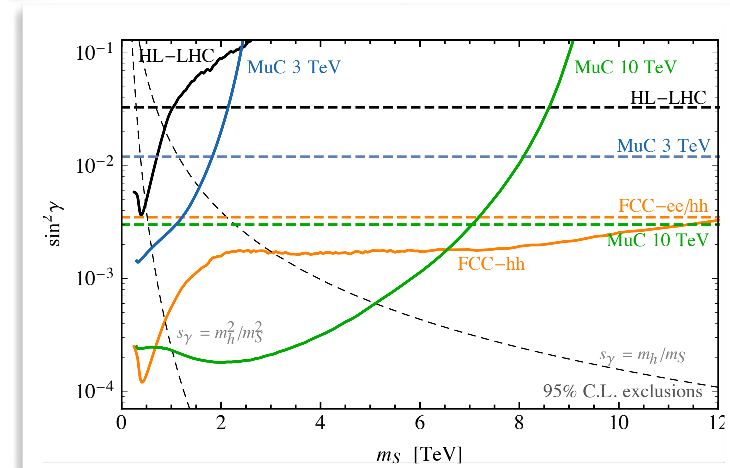


These searches can, for instance, advance probes of (un)-Natural EWSB by one or two orders of magnitude

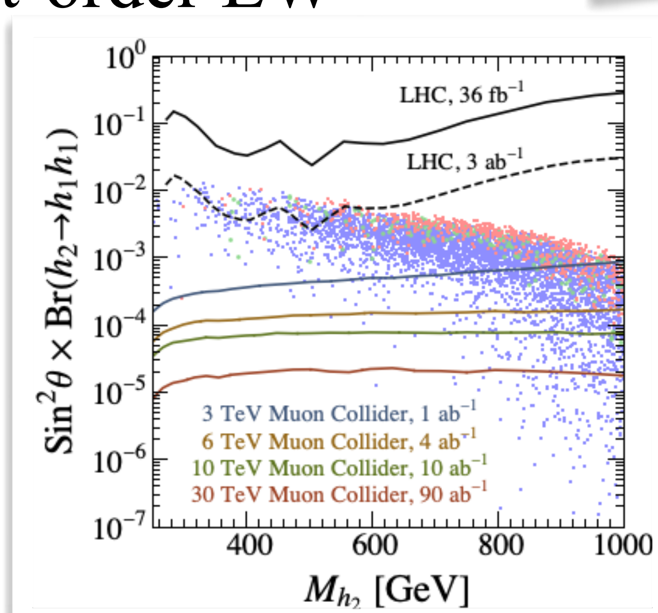


Vector Bosons Fusion: sensitive to EW-neutral **Higgs-Portal** particles

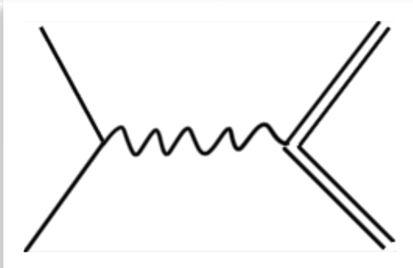
$|H|^2 \cdot X^2$; or $|H|^2 \cdot X$



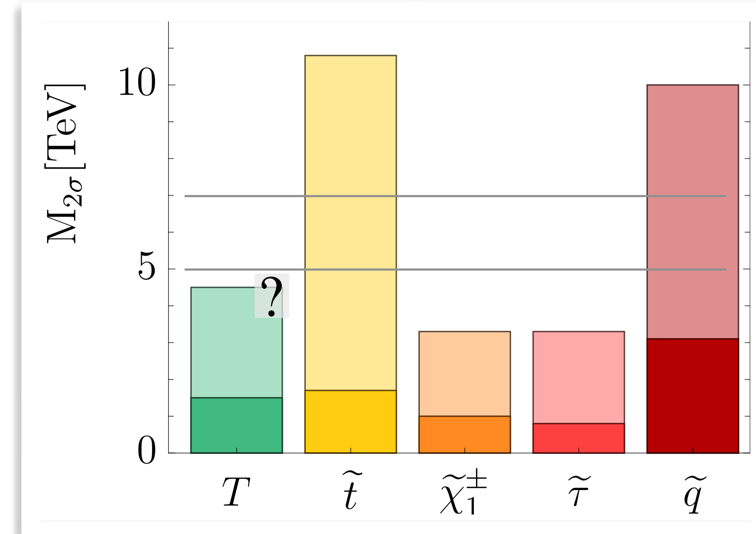
This will, for instance, probe conclusively extended Higgs sectors that produces strong first-order EW phase transition in the early Universe



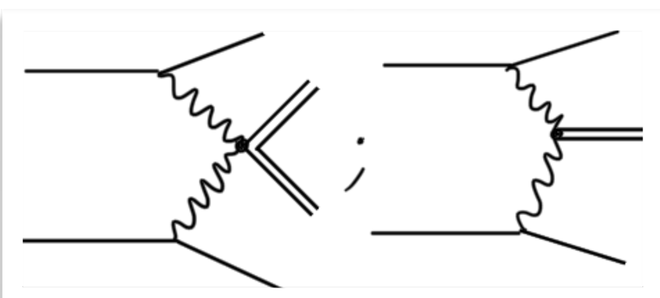
Direct searches



μμ annihilation: copious production of **EW-charged particles** up to $E_{cm}/2$

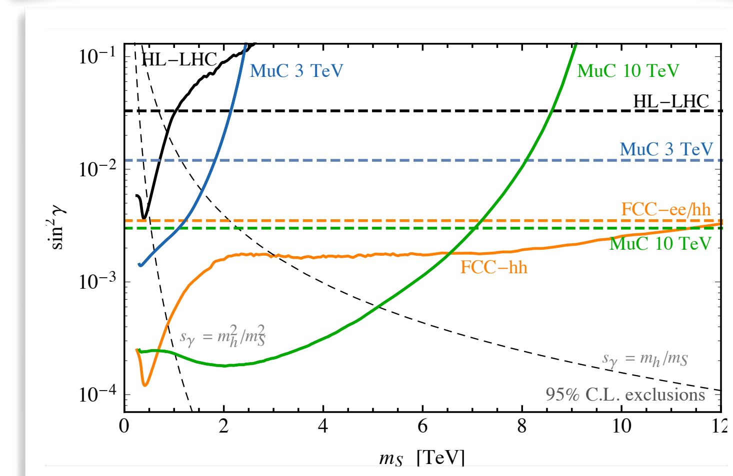


These searches can, for instance, advance probes of (un)-Natural EWSB by one or two orders of magnitude



Vector Bosons Fusion: sensitive to EW-neutral **Higgs-Portal** particles

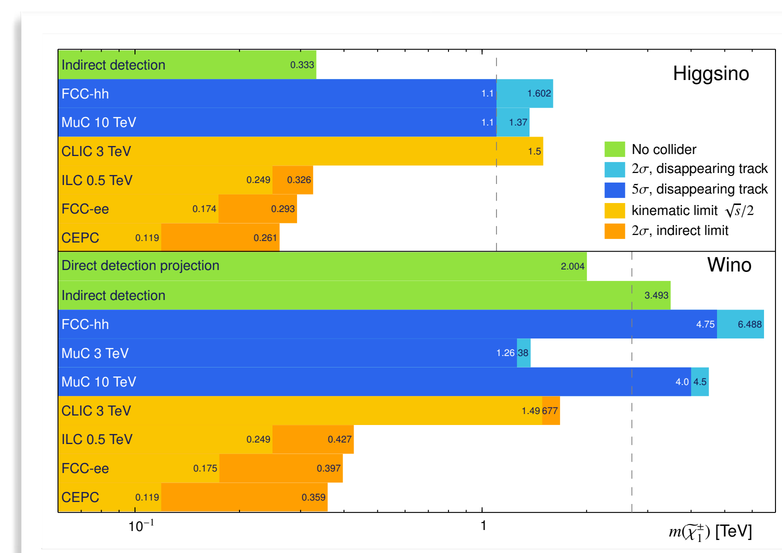
$$|H|^2 X^2 \;; \text{ or } |H|^2 X$$

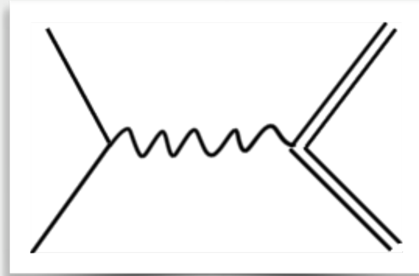


This will, for instance, probe conclusively extended Higgs sectors that produces strong first-order EW phase transition in the early Universe

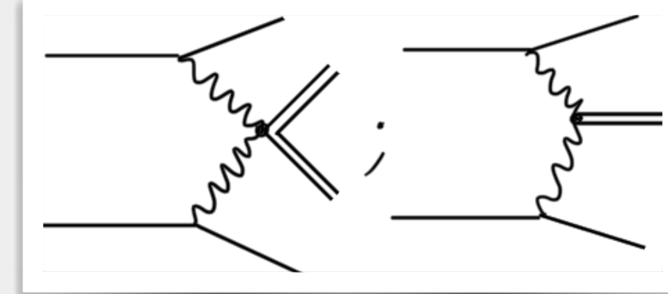
WIMP or WIMP-like DM search program:

- Disappearing tracks
- Mono-X and indirect searches
- Higgs-portal DM in VBF
- **Thermal Wino and Higgsino discovery**





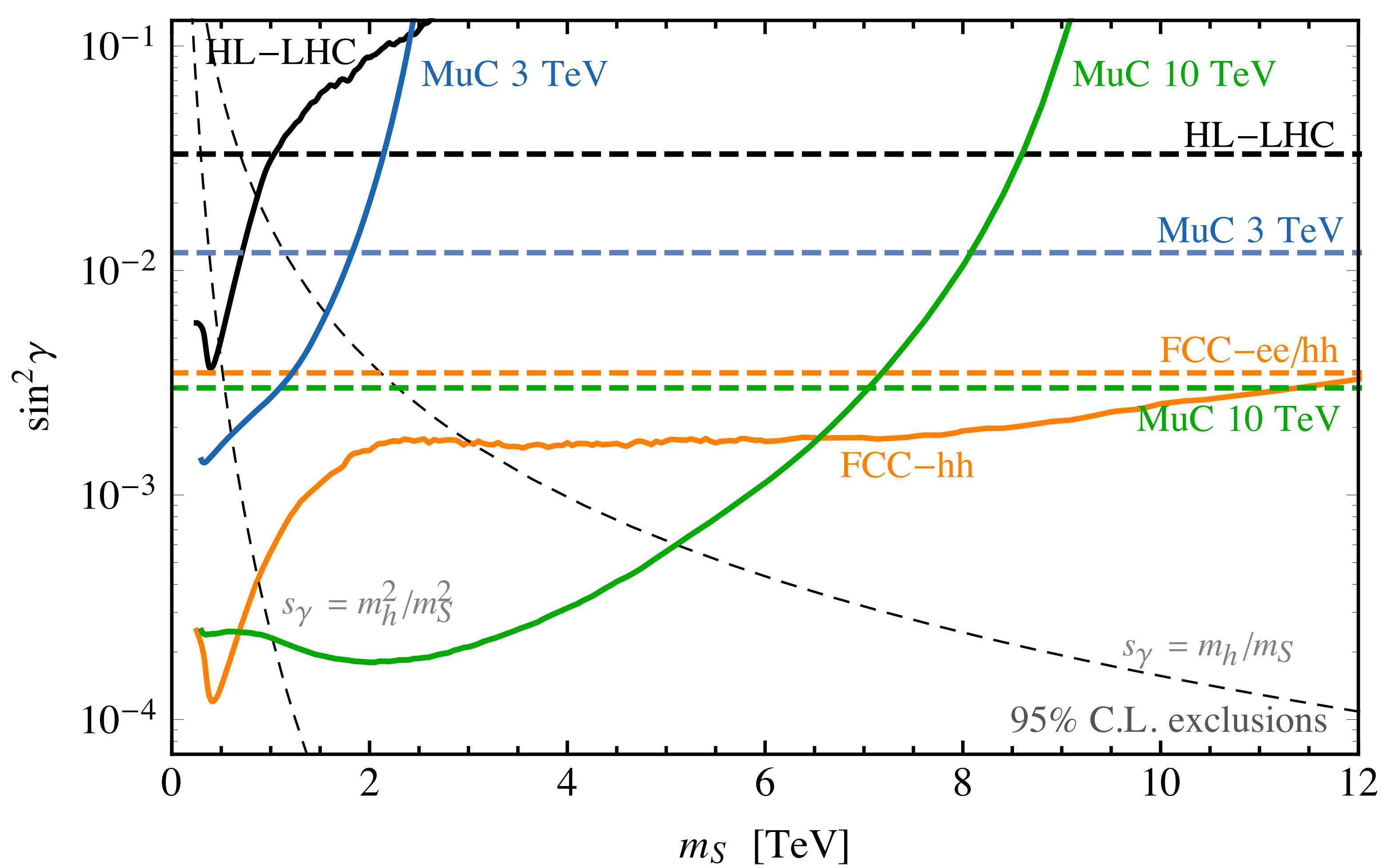
Direct searches

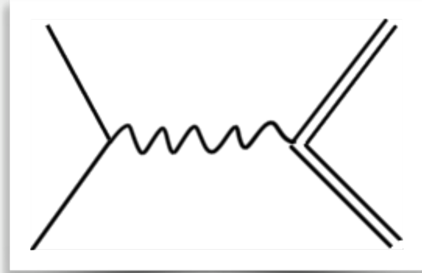


Much work is needed!:

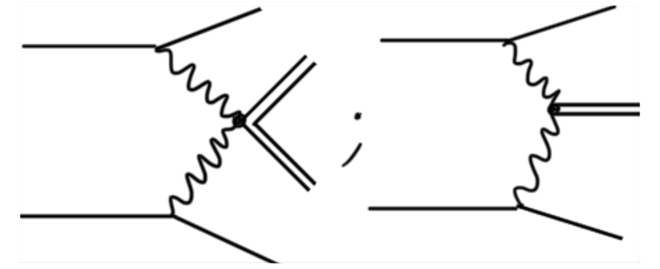
BSM models feature many particles, and many signatures.
Detailed study will enable:

- Compare different search strategies and study their complementarity
- Study muon collider discovery and characterisation perspectives
- Sound comparison with FCC: not signature- but model-based





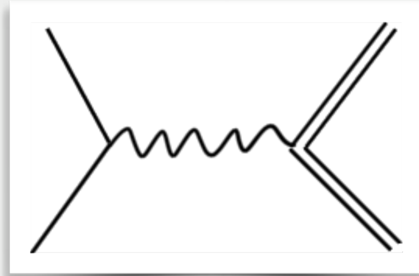
Direct searches



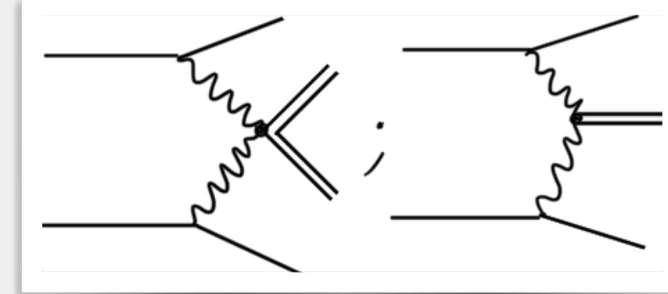
Much work is needed!:

Pheno challenges:

- Order-one **EW radiation effects**. Leading to novel signatures!
  The "simplest" Z' to di-lepton, at 10 TeV, looks like this:



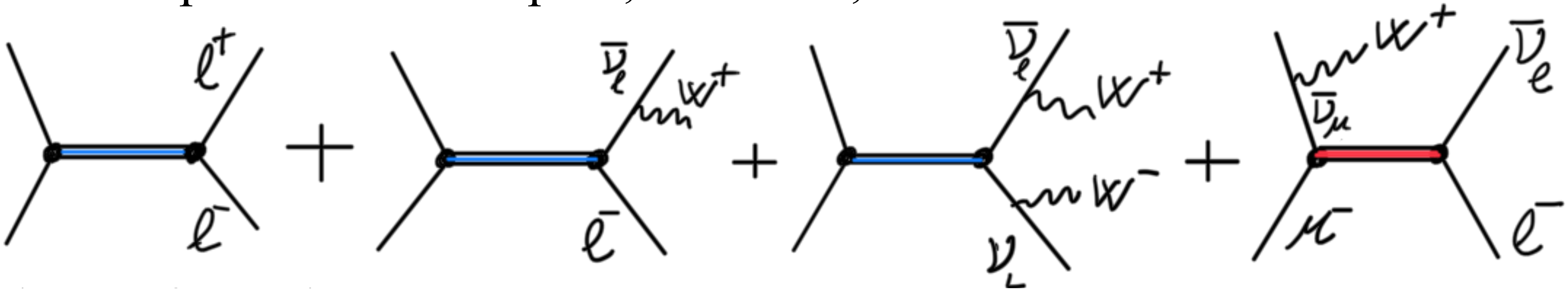
Direct searches

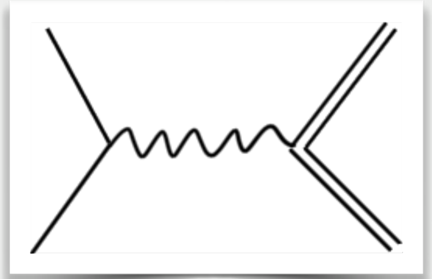


Much work is needed!:

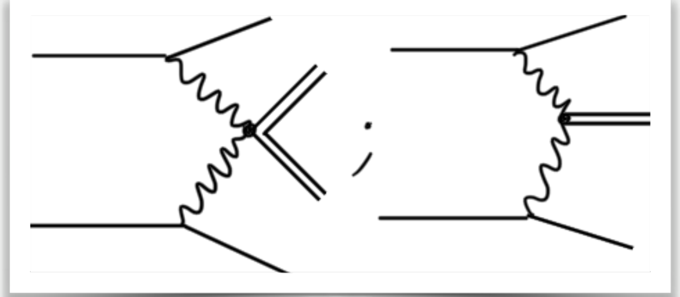
Pheno challenges:

- Order-one **EW radiation effects**. Leading to novel signatures! The “simplest” Z’ to di-lepton, at 10 TeV, looks like this:





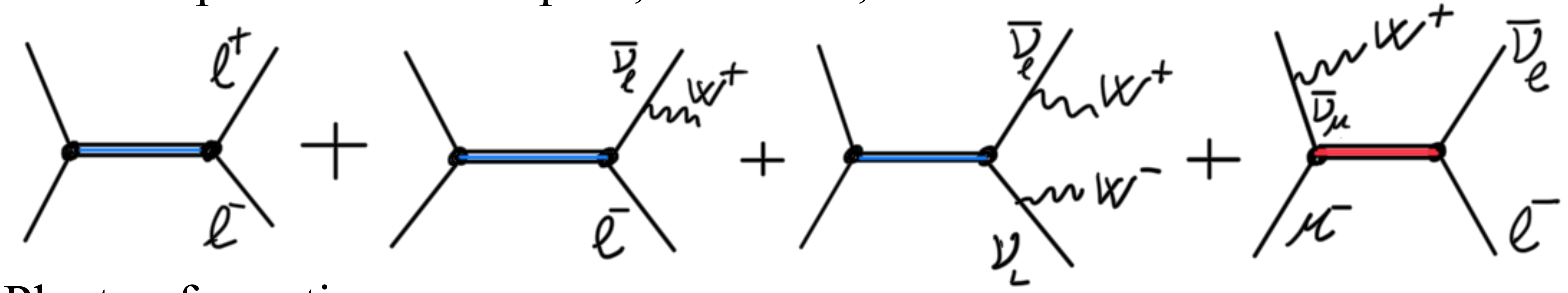
Direct searches



Much work is needed!:

Pheno challenges:

- Order-one **EW radiation effects**. Leading to novel signatures!
  The “simplest” Z’ to di-lepton, at 10 TeV, looks like this:

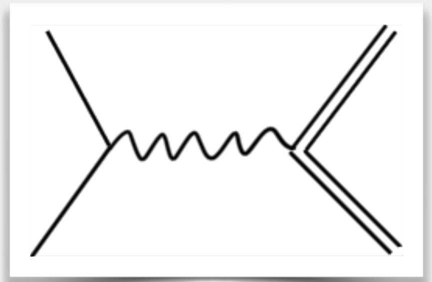


Plenty of questions:

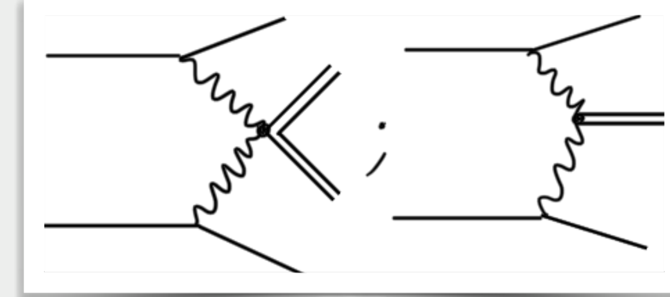
Will we resolve the vector bosons?

Need new concept of electroweak jets?

Can we tell if decays to lepton or neutrino, tell if neutral or charged resonance?



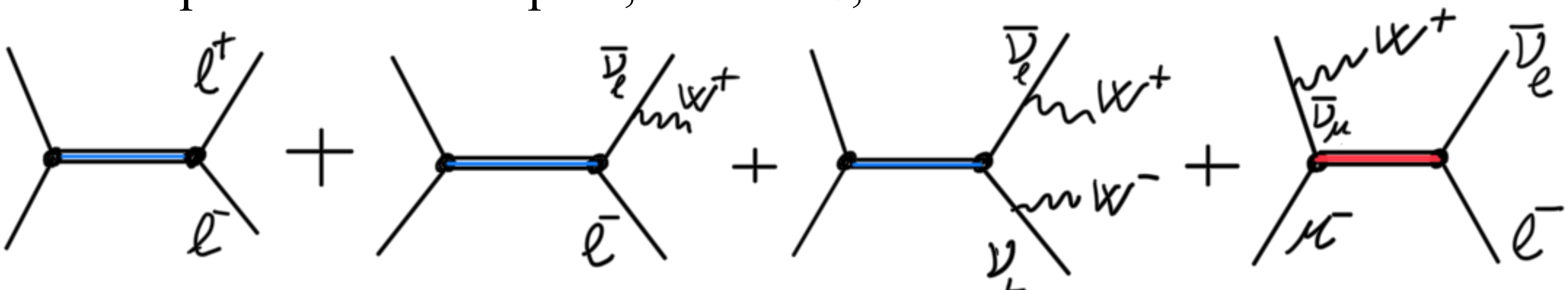
Direct searches



Much work is needed!:

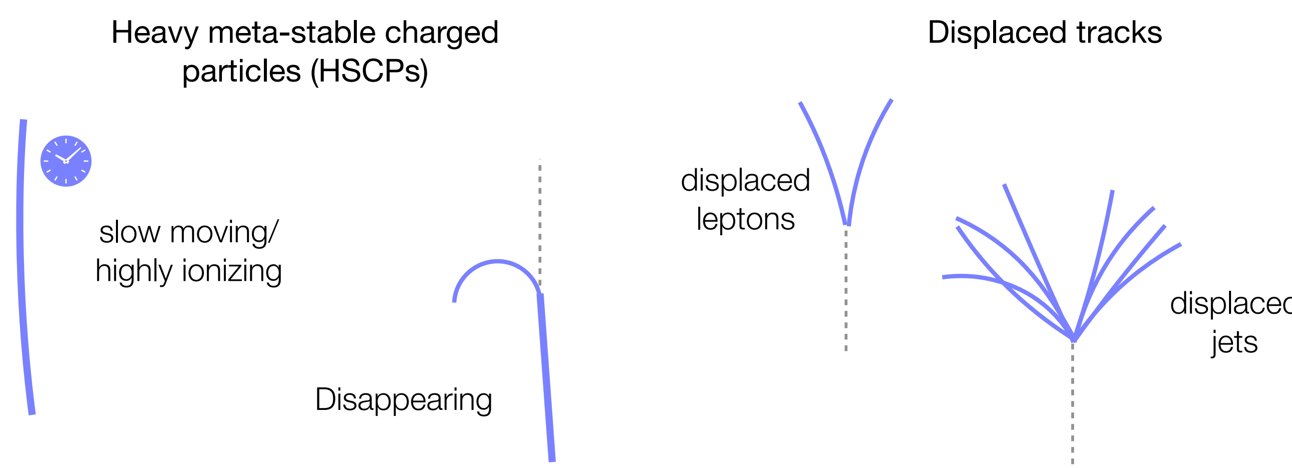
Pheno challenges:

- Order-one **EW radiation effects**. Leading to novel signatures!
  The “simplest” Z’ to di-lepton, at 10 TeV, looks like this:

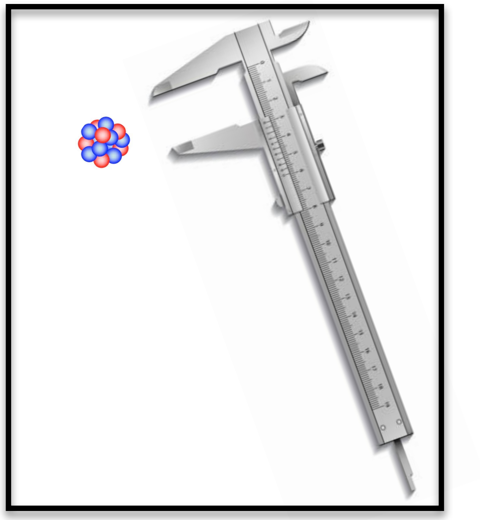


  Plenty of questions:
  Will we resolve the vector bosons?
  Need new concept of electroweak jets?
  Can we tell if decays to lepton or neutrino, tell if neutral or charged resonance?

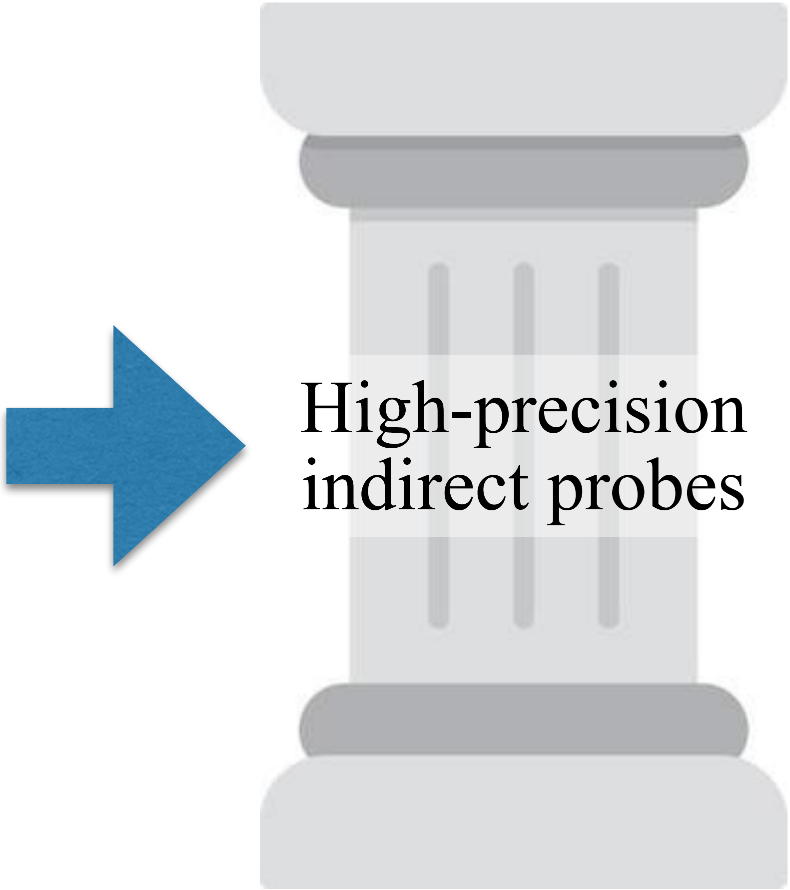
- Long-lived particles study to inform MuC detector design.
  New challenges from “BIB” (see later)

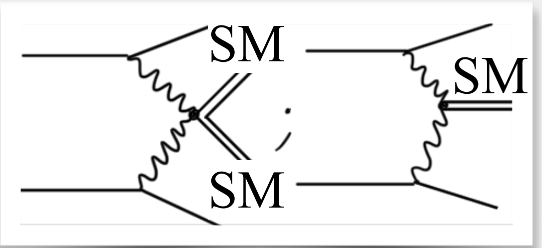


High-precision indirect probes

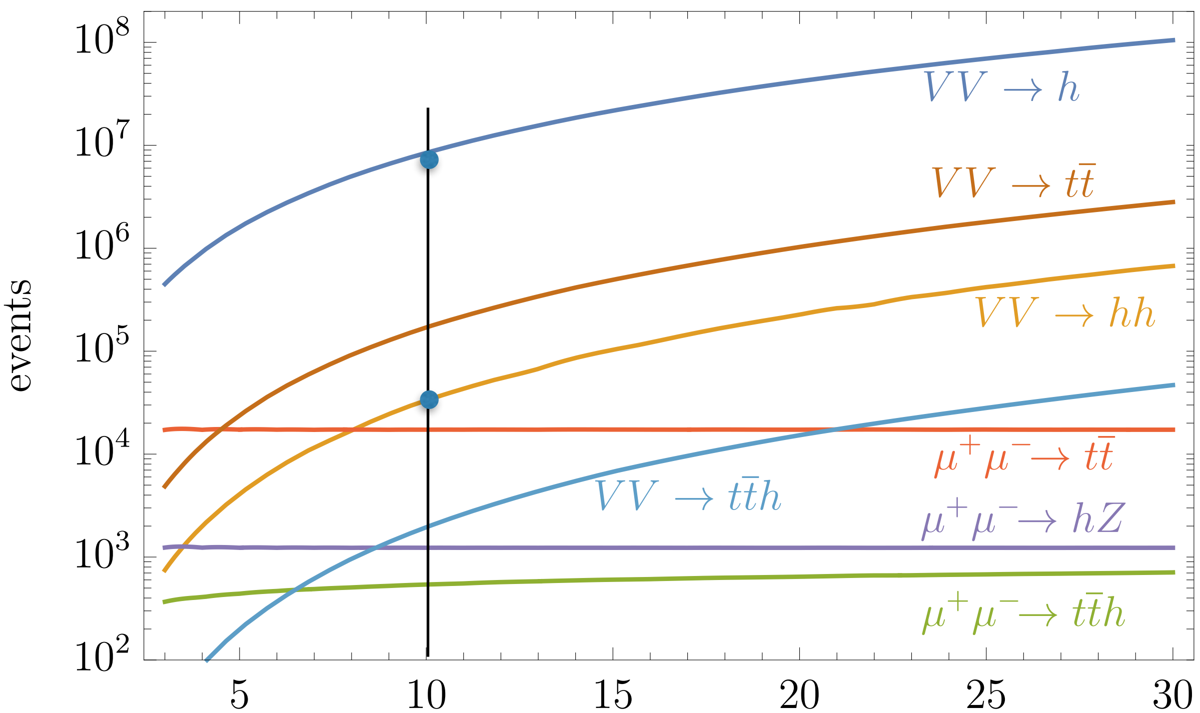


Precision



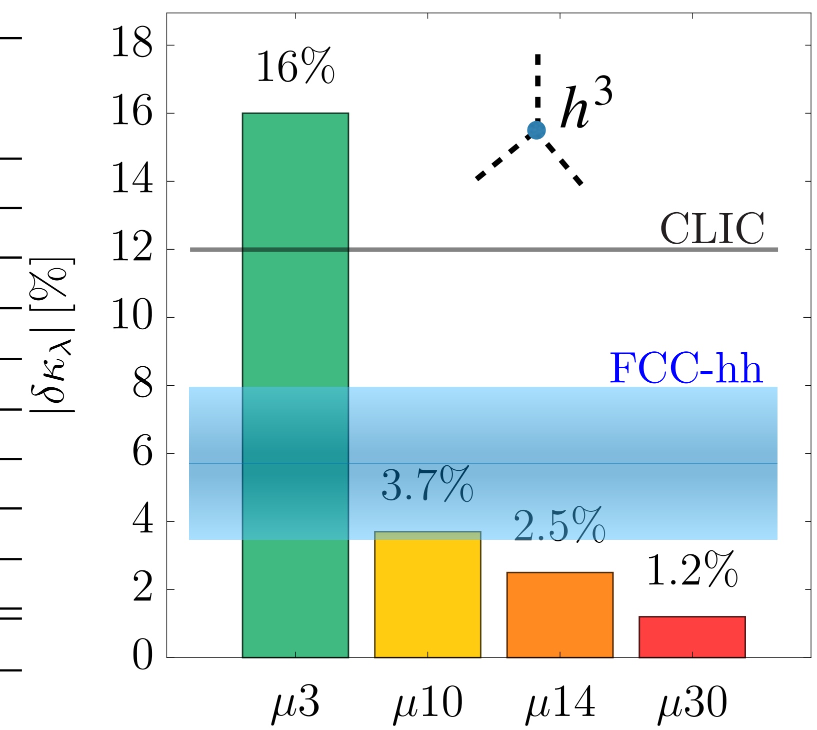


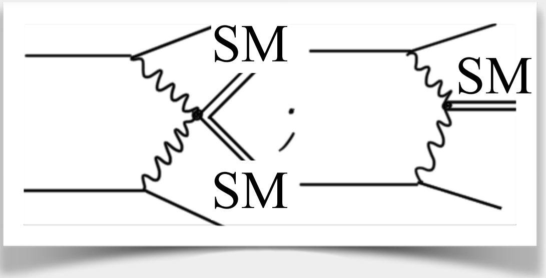
High-precision indirect probes



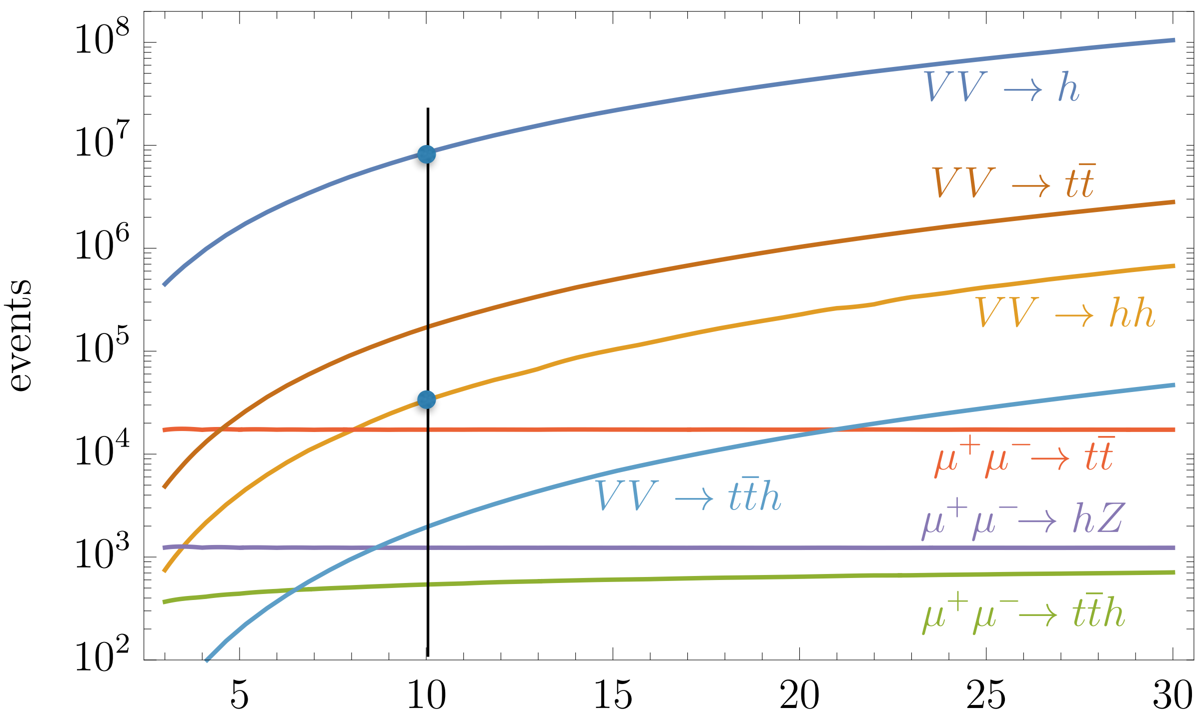
	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for μ collider



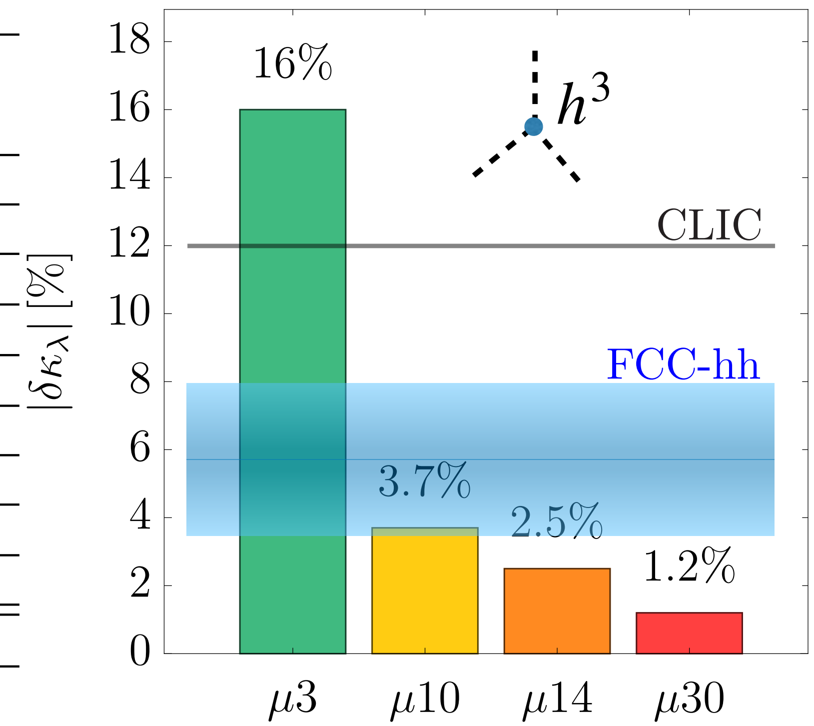


High-precision indirect probes



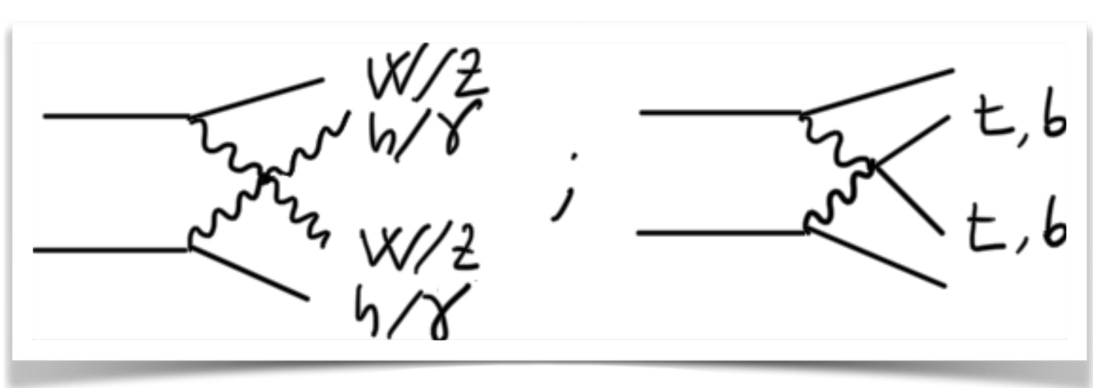
	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for μ collider



Precision To-Do List:

- Will per-mille level predictions for Higgs physics be possible? In spite of possibly large EW loops?
- Study other precision measurements. Vector Boson Scattering defines a rich set of processes, much desired at LHC but challenging because of QCD. MuC will do much better and at higher energy.

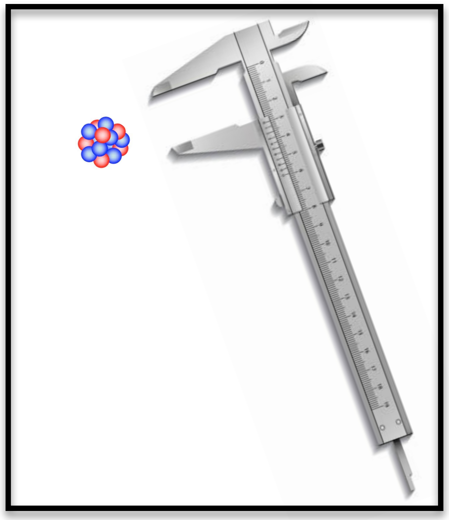


Physics Opportunities

The muon collider combines pp and ee advantages:

- High available energy for new heavy particles production
- High available statistics for precise measurements (and no QCD bck)

Energy



Precision

Physics Opportunities

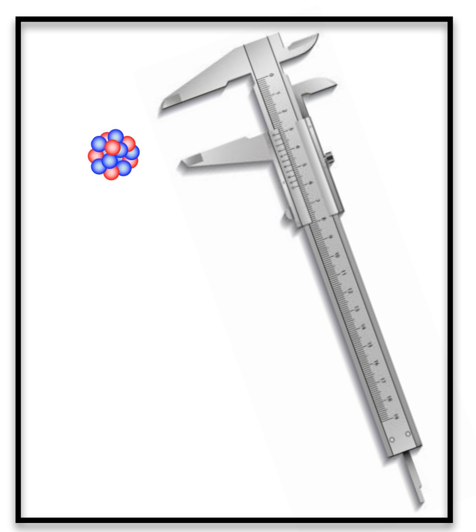
The muon collider combines pp and ee advantages:

- High available energy for new heavy particles production
- High available statistics for precise measurements (and no QCD bck)

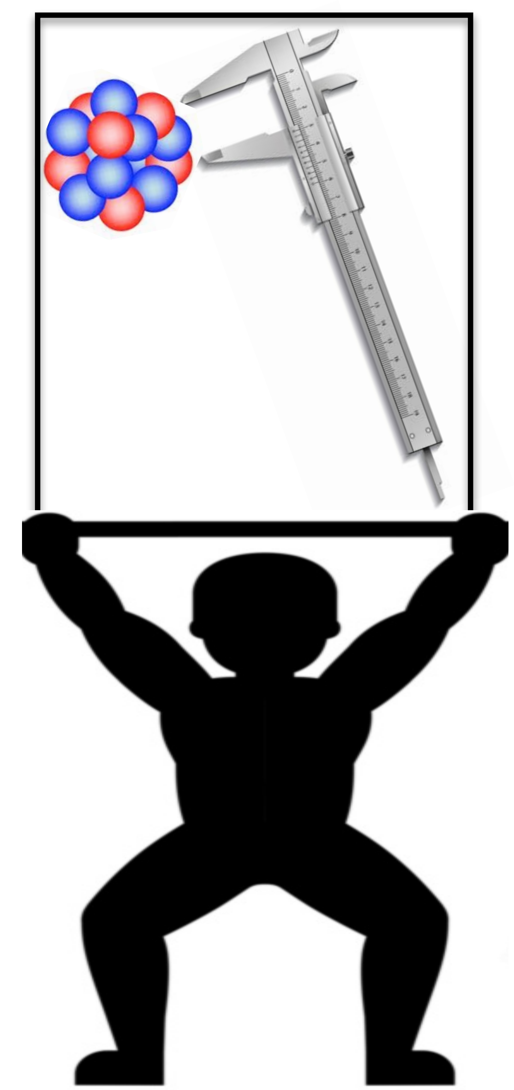
Furthermore:

- Can measure processes of very high energy

Energy



Precision

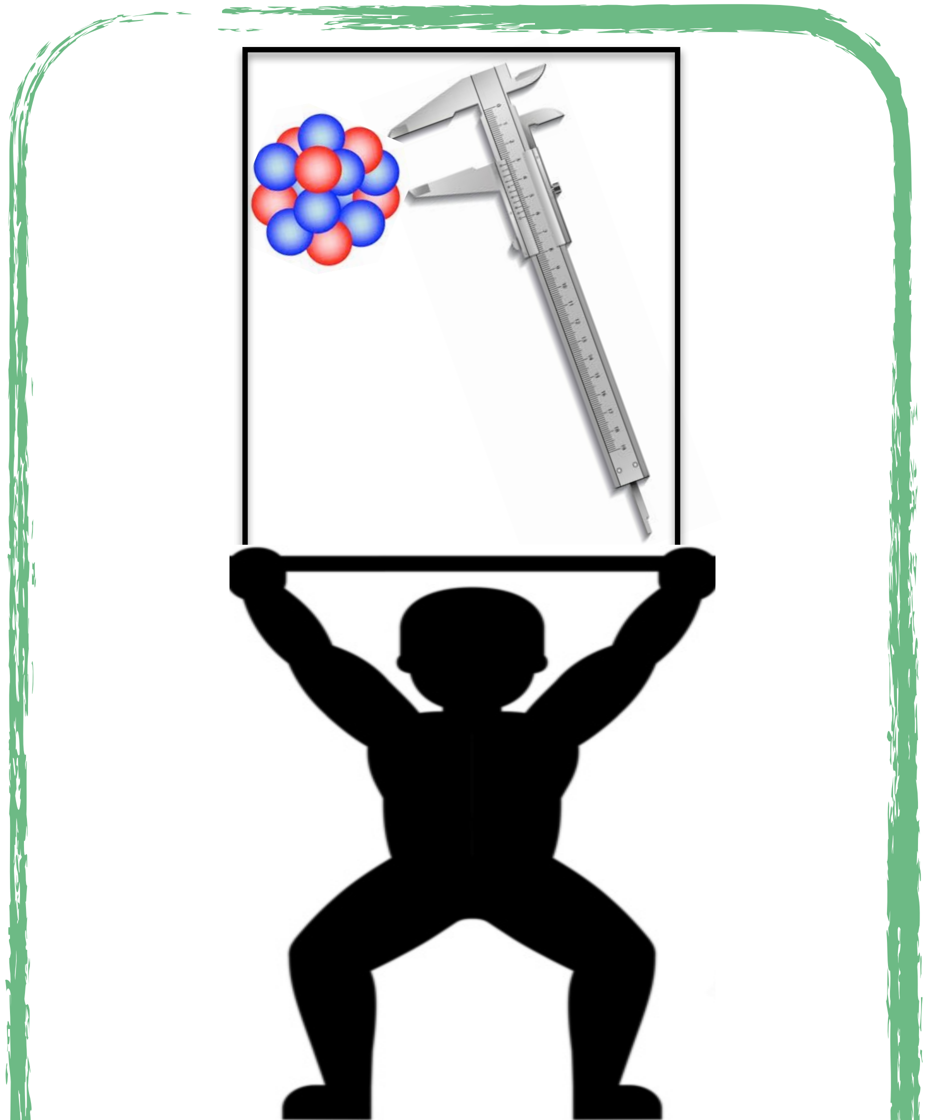


High-energy Precision

Physics Opportunities

Many discoveries came neither from new particle detection, nor from extreme precision, **but needed energy**. E.g.:

- Neutral Currents
- Proton Compositeness



Physics Opportunities

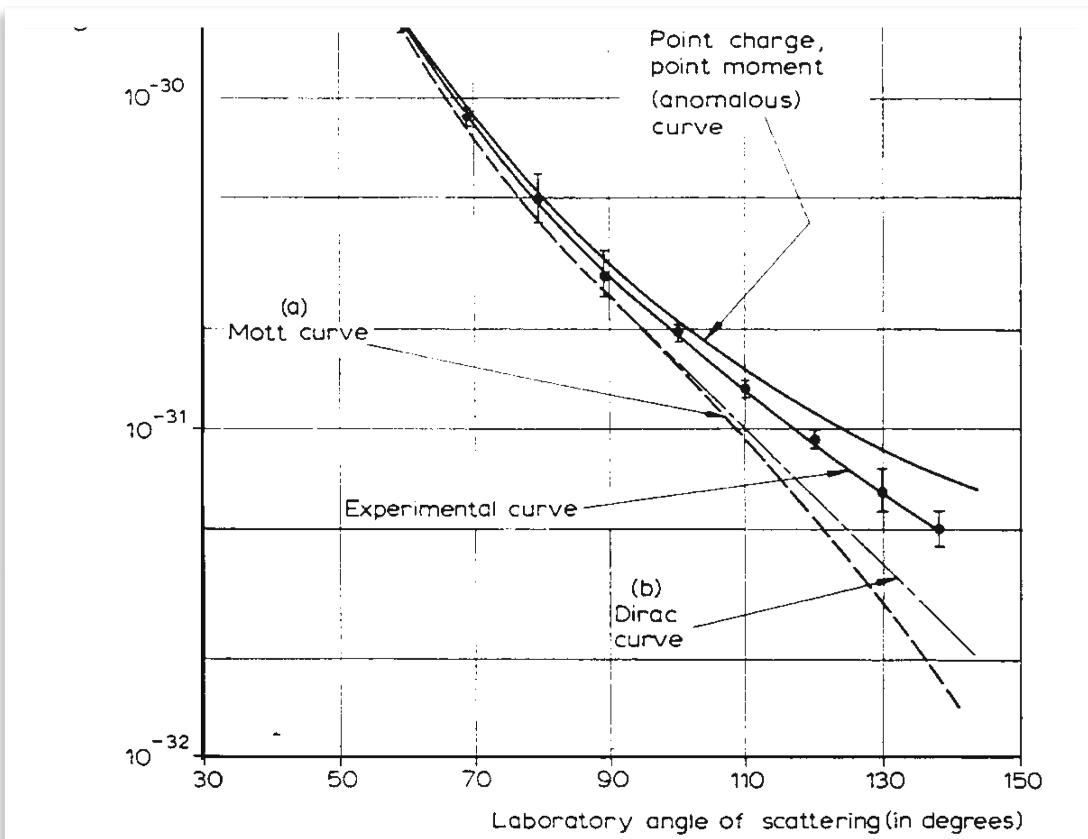
Many discoveries came neither from new particle detection, nor from extreme precision, **but needed energy**. E.g.:

- Neutral Currents
- Proton Compositeness

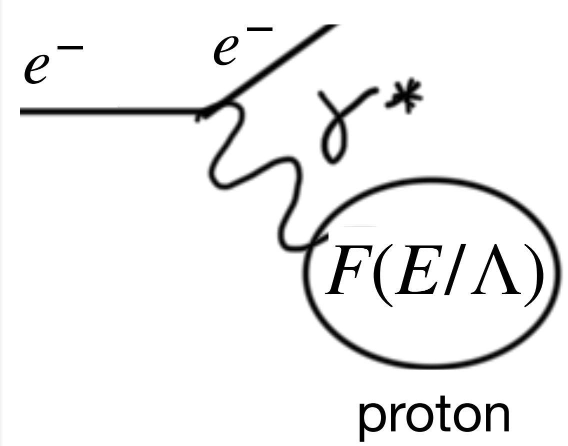
Proton compositeness discovery:

- Order 10% departure from point-like prediction.
- Visible form-factor effects required **large energy**

$$E \nearrow \Lambda \sim 1/r_p$$

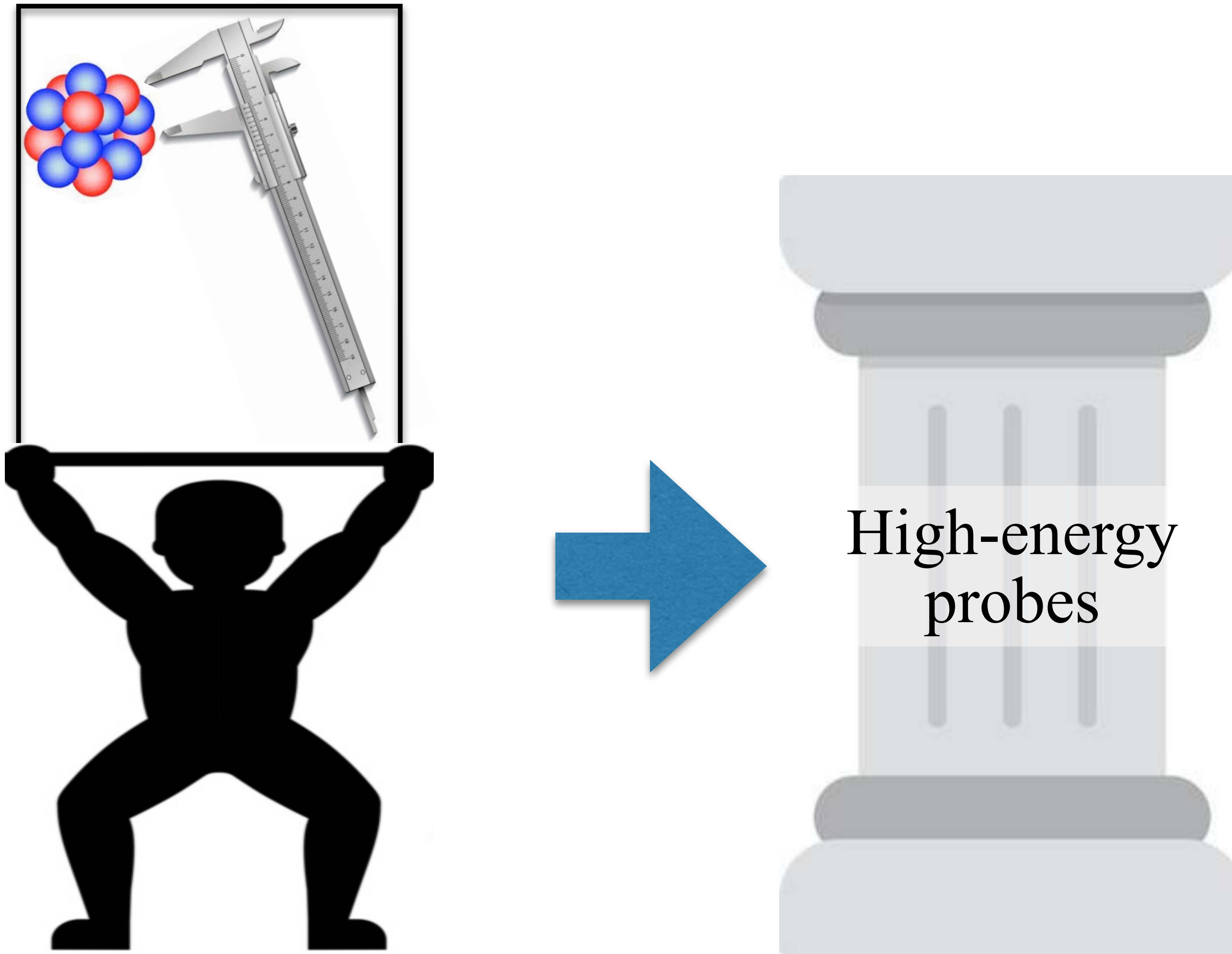


Electron scattering from the proton at an incident energy of 188 MeV.

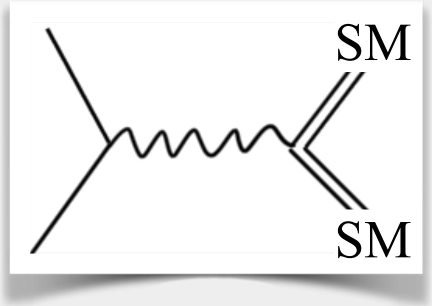


High-energy Precision

High-energy probes



High-energy Precision



High-energy probes

As simple as this:

$$\frac{\Delta\sigma(E)}{\sigma_{\rm SM}(E)} \propto \frac{E^2}{\Lambda^2_{\rm BSM}} \overset{[\textbf{say, } \Lambda_{\rm BSM} = \textbf{100 TeV}]}{=}$$

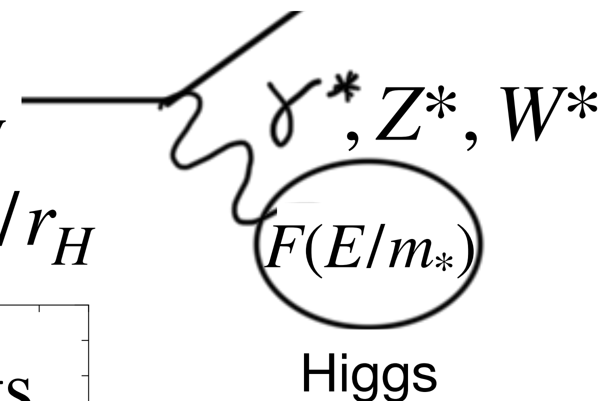
10^{-6} at EW [FCC-ee] energies

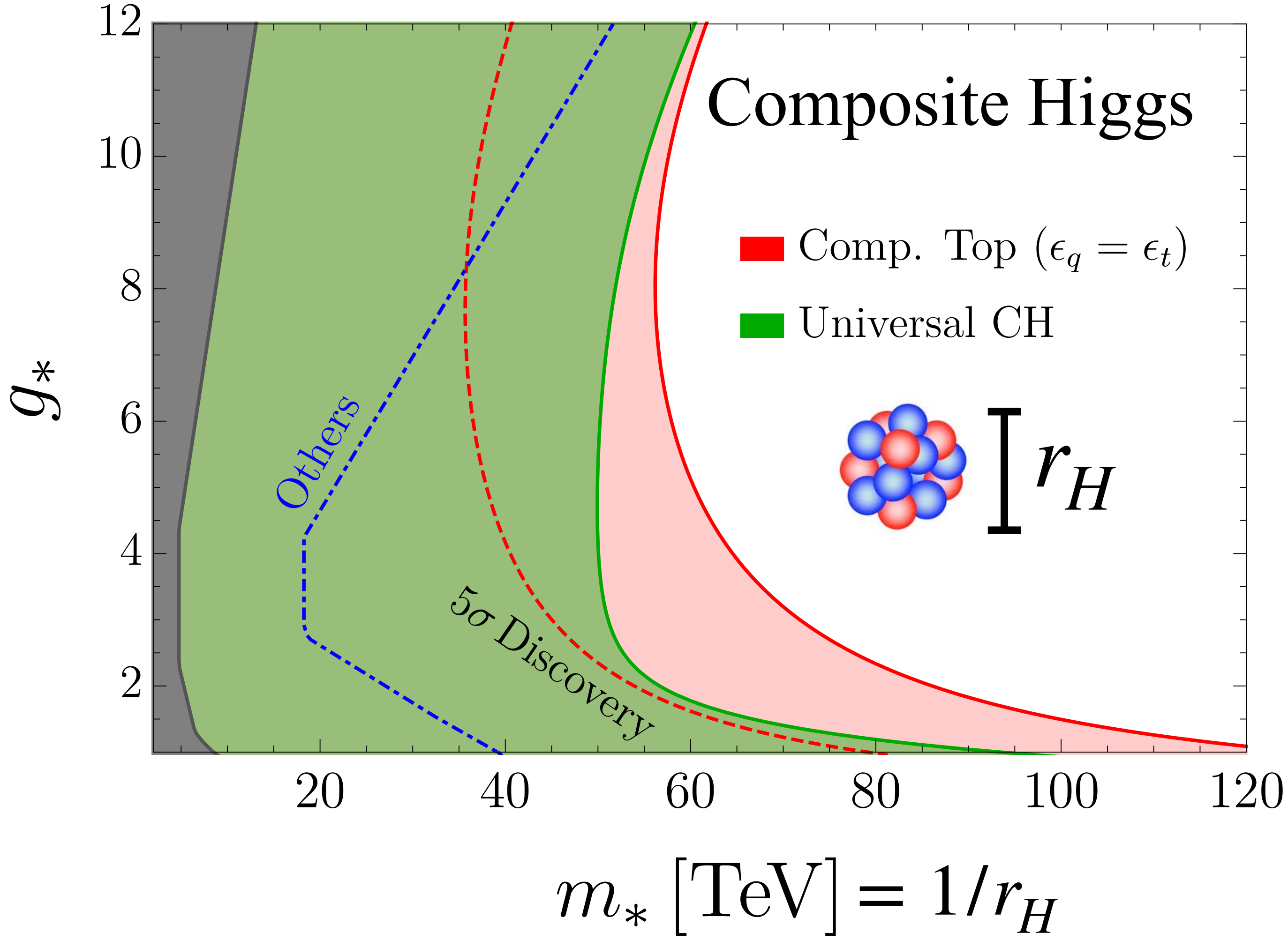
10^{-2} at **muon collider** energies

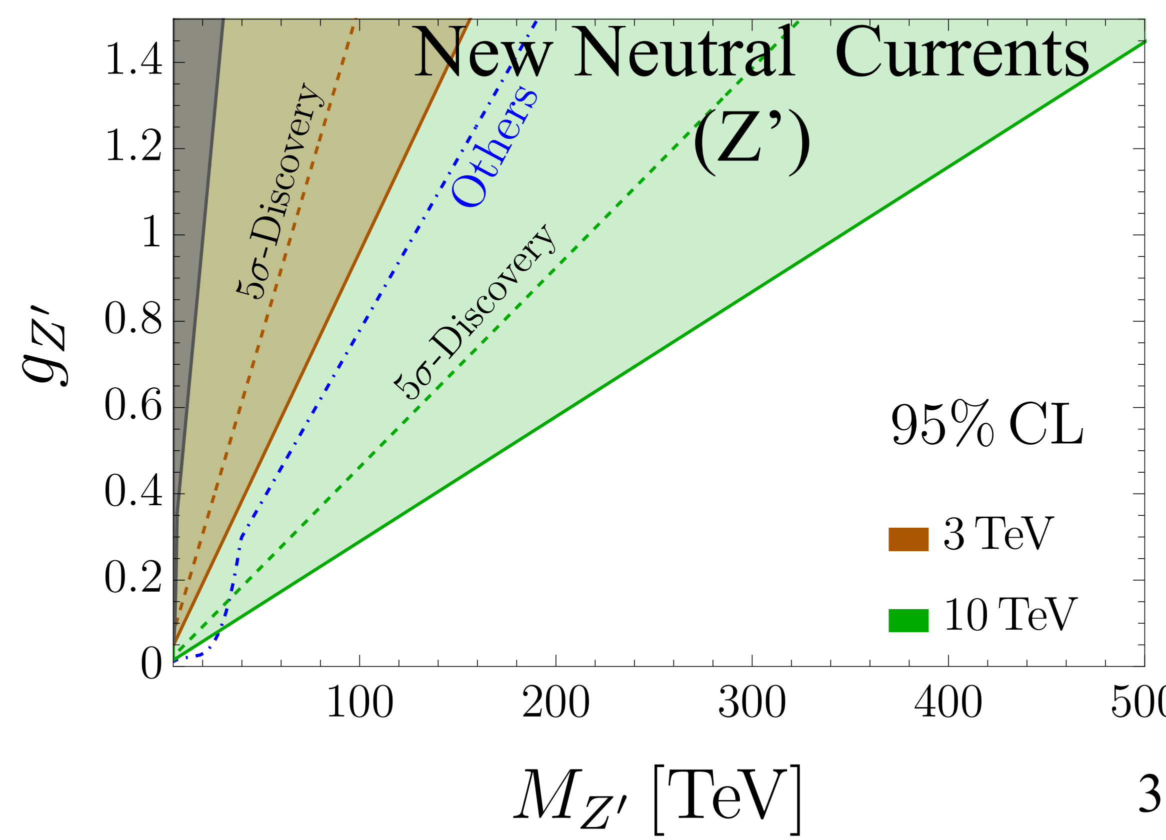
Or even simpler:

Same as proton, with **larger energy**

$E \nearrow m_* \sim 1/r_H$







The SM Physics Case

The muon collider will **probe a new regime of EW force:**

$$\mathbf{E \gg m_W}$$

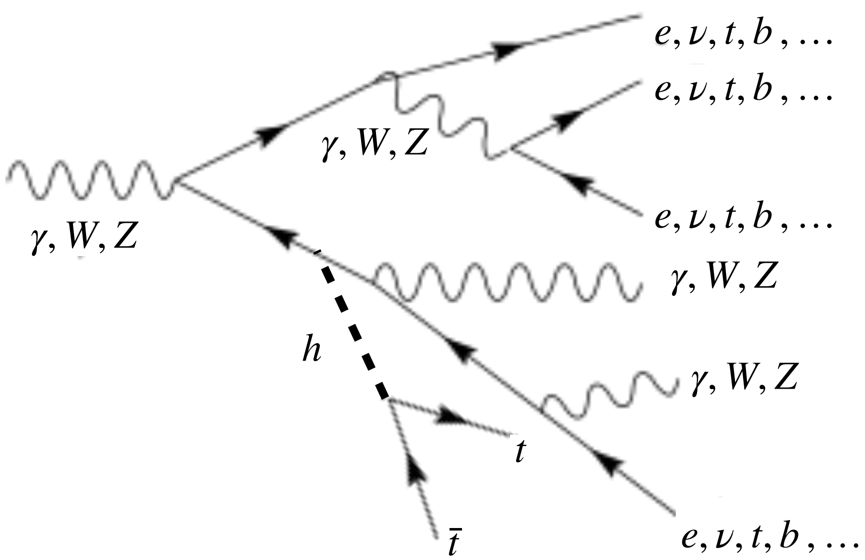
Plenty of cool things will happen:

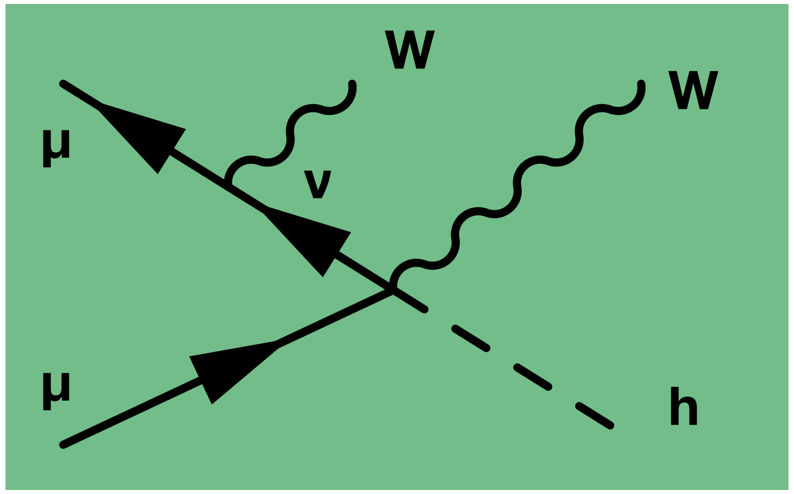
Electroweak Restoration. The $SU(2) \times U(1)$ group emerging, finally!

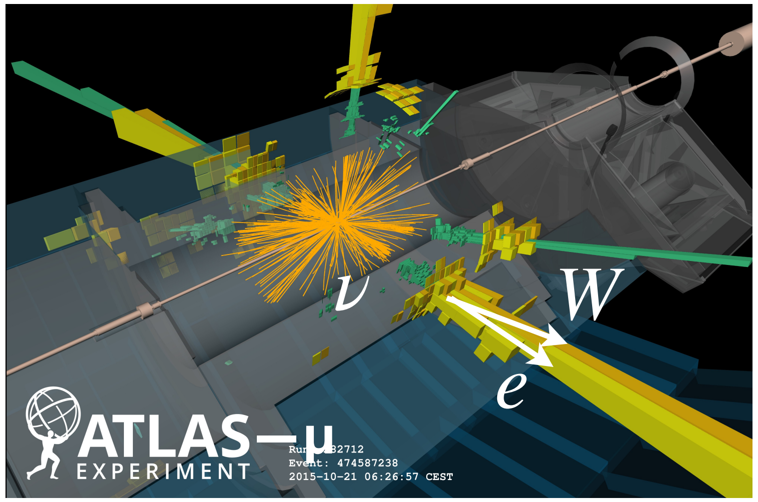
Electroweak Radiation in nearly massless broken gauge theory.
Never observed, never computed (and we don't know how!)

The **partonic content of the muon**: EW bosons, neutrinos, gluons, tops, …
Copious **scattering of 5 TeV neutrinos!**

The **particle content of partons:** e.g., find Higgs in tops, or in W's, etc
Neutrino jets will be observed, and many more cool things

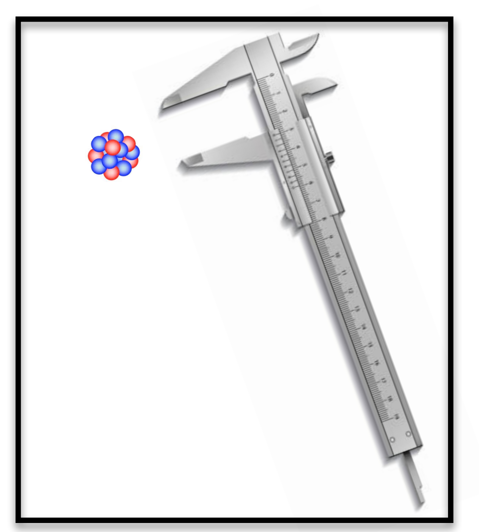




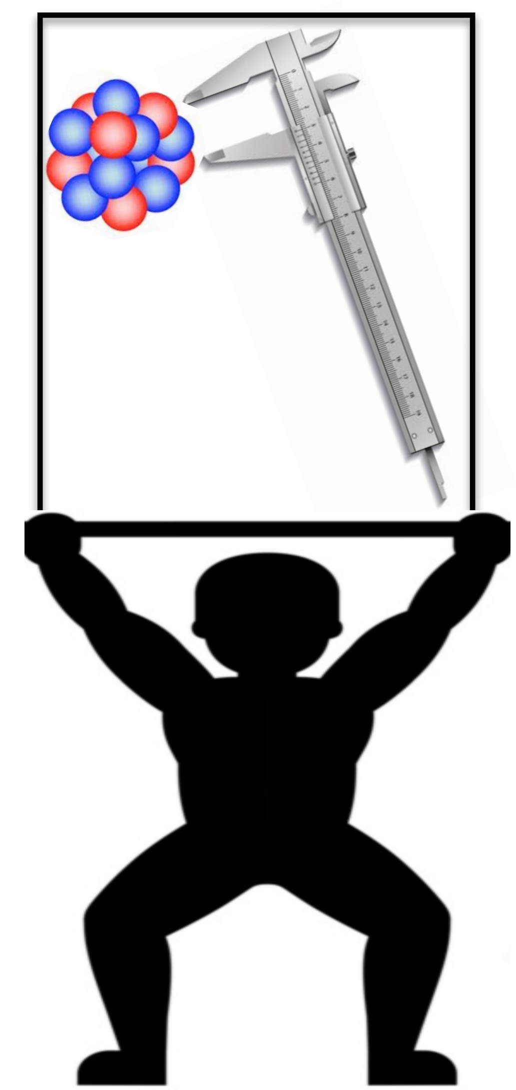


Physics Opportunities

Energy



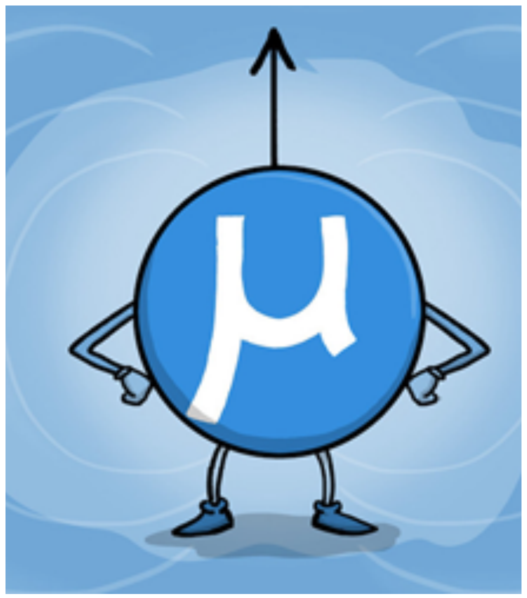
Precision

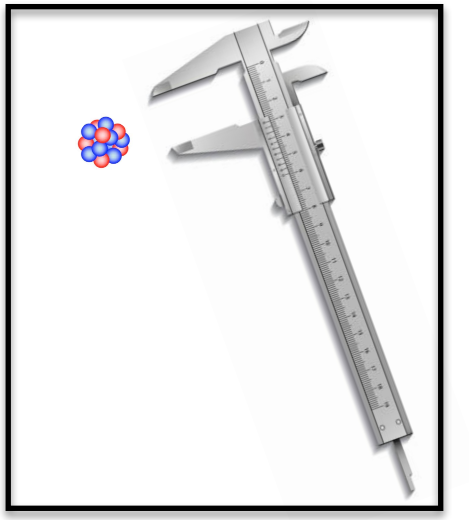


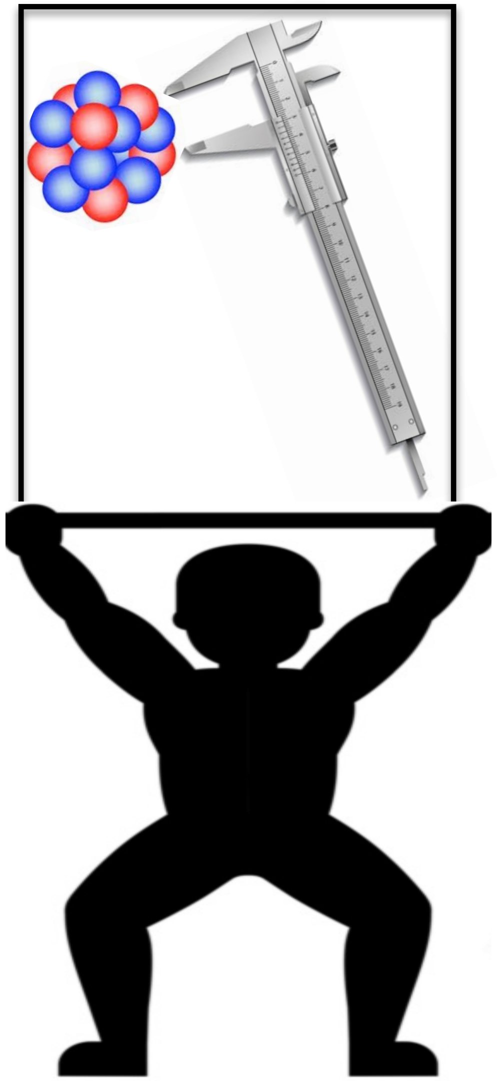
High-energy Precision

Physics Opportunities

Muons!!







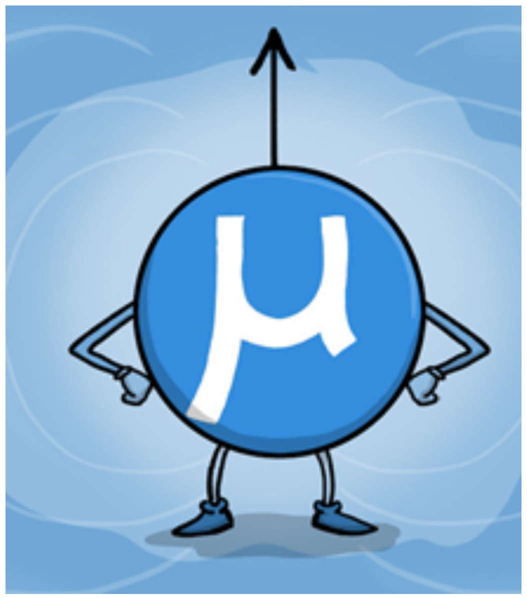
Energy

Precision

High-energy Precision

Physics Opportunities

Muons!!

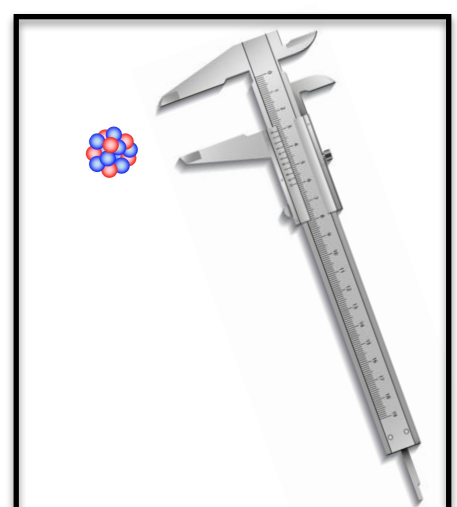


Muons colliding for first time

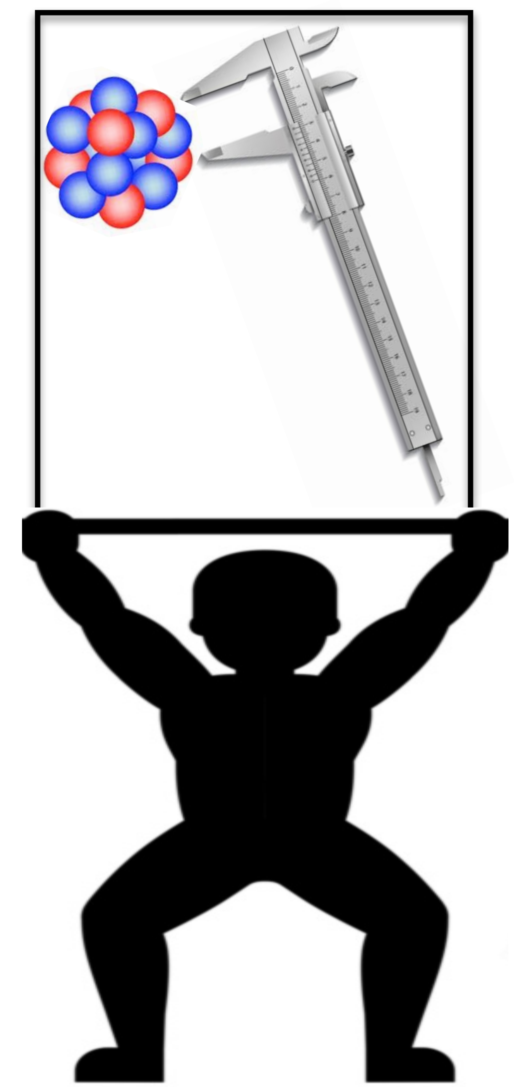
Self-evident potential of exploration.

Novelty and **challenge** for accelerator physics, technology, and detector, **make such big-scale project plausible!**

Energy



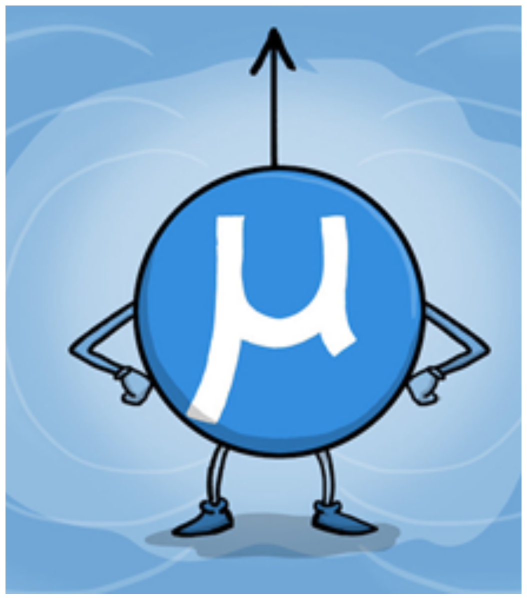
Precision



High-energy Precision

Physics Opportunities

Muons!!



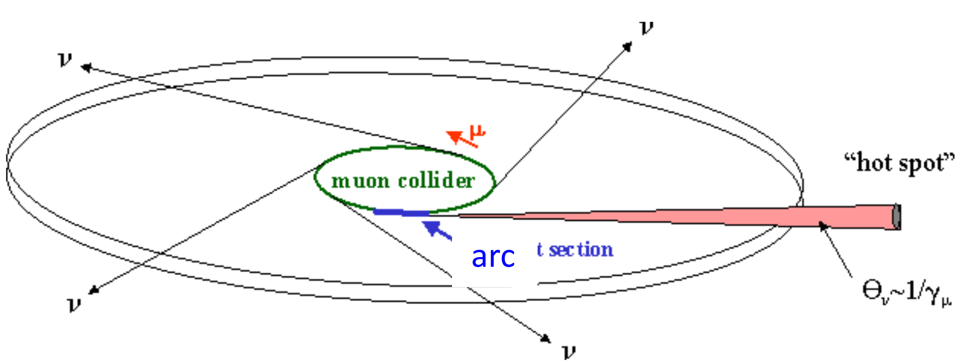
Muons colliding for first time

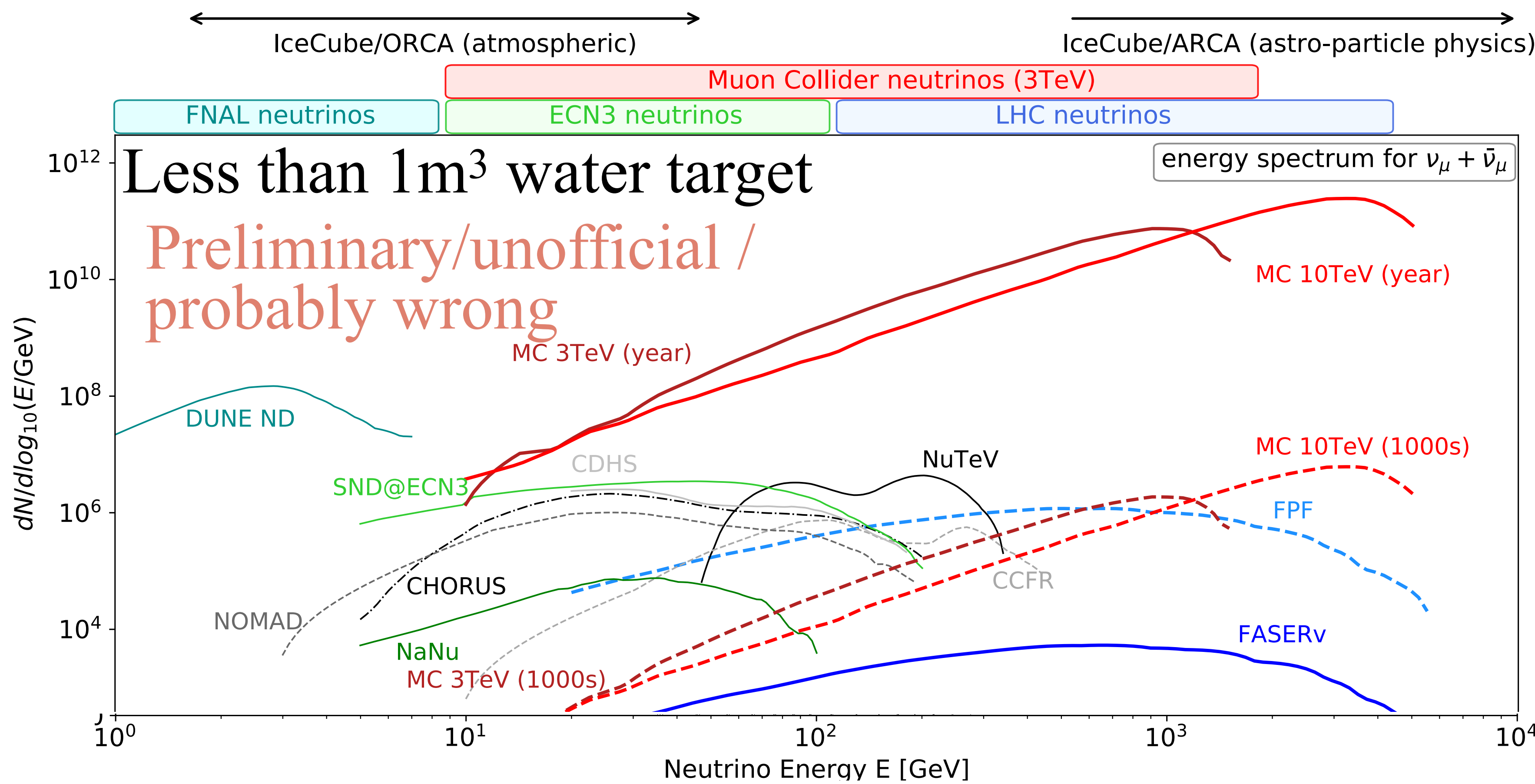
Self-evident potential of exploration.

Novelty and **challenge** for accelerator physics, technology, and detector, **make such big-scale project plausible!**

Muons decay to neutrinos:

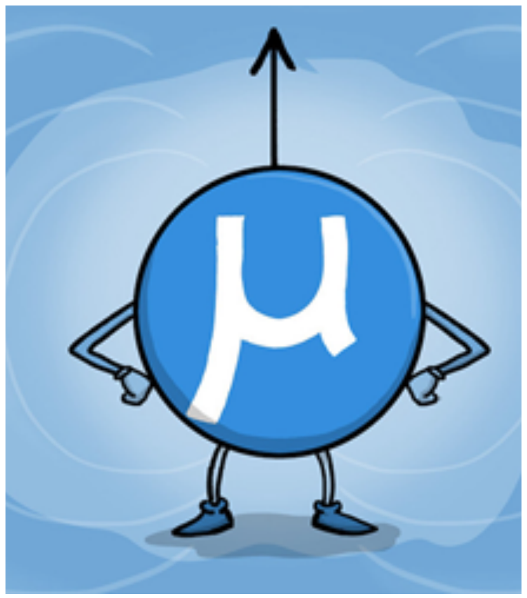
Collimated, perfectly known, TeV-energy neutrino beams!





Physics Opportunities

Muons!!



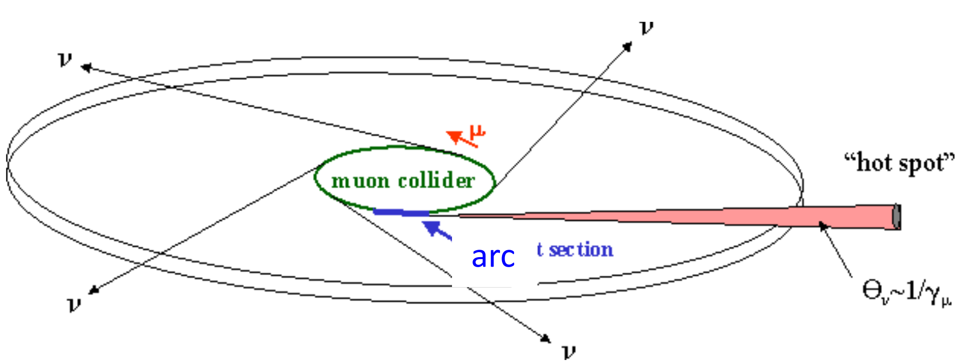
Muons colliding for first time

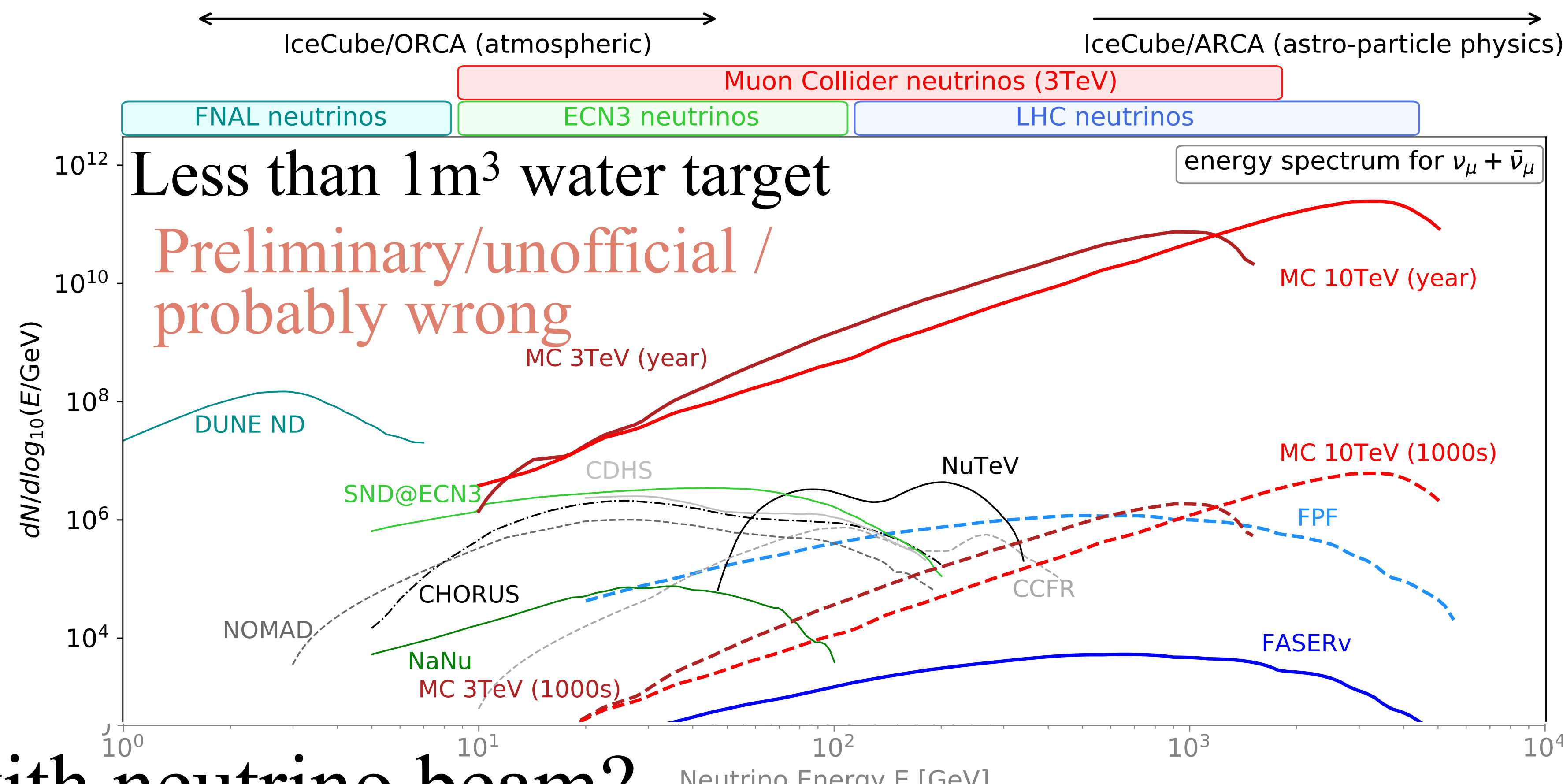
Self-evident potential of exploration.

Novelty and **challenge** for accelerator physics, technology, and detector, **make such big-scale project plausible!**

Muons decay to neutrinos:

Collimated, perfectly known, TeV-energy neutrino beams!





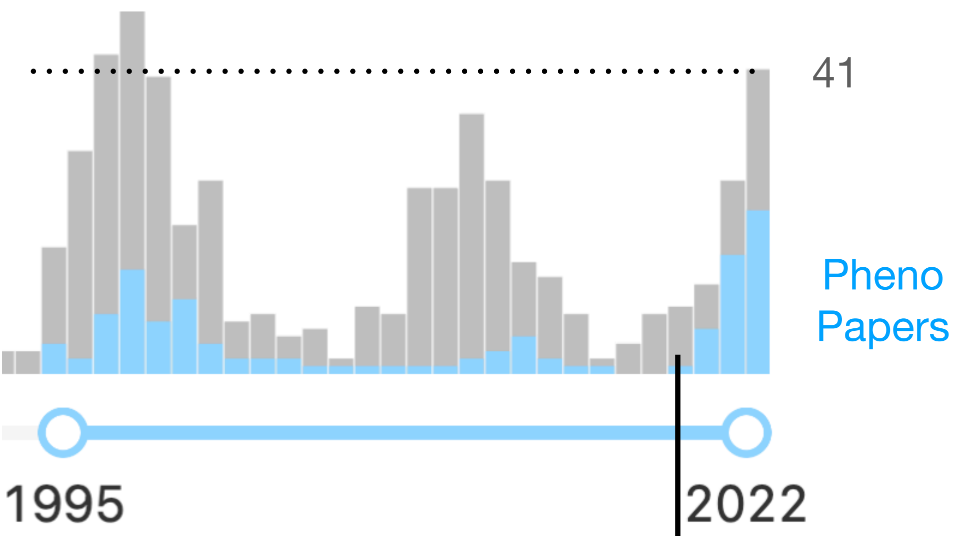
Which experiments with neutrino beam?

Statistics could enable ground-breaking PDF program

What about neutrino physics? Which BSM opportunities?

Why Working on the Muon Collider

A **new interest** on muon colliders, **not** a **renewed** one



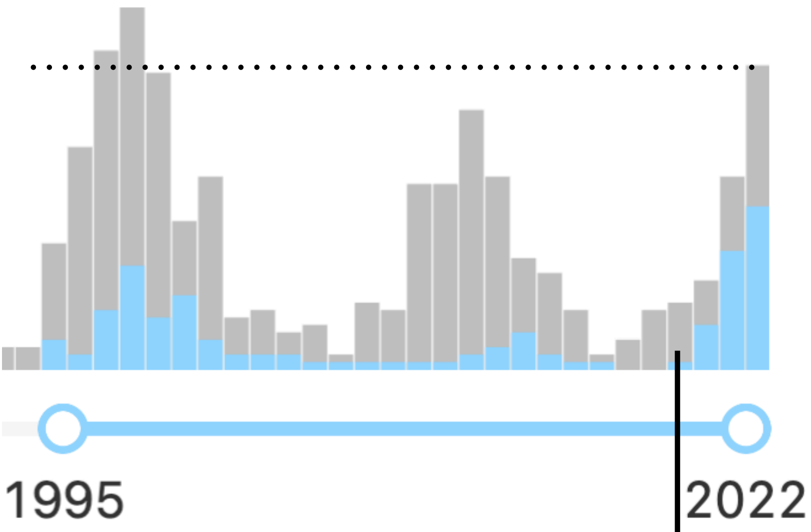
MuC WG EU Strat. Report: 2019

"A 10-TeV scale muon collider with sufficient integrated luminosity provides an energy reach similar to that of a 100 TeV proton-proton collider. [...] muon and hadron colliders have similar reach and can significantly constrain scenarios motivated by the naturalness principle. [...] Multi-TeV muon colliders will have the benefit of excellent signal to background [...] One of the key measurements from the multi-TeV colliders is the one of the Higgs self-coupling to a precision of a few percent, and the scanning of the Higgs potential."

From Snowmass EF report. Based on 2 IMCC + 1 MuC Forum reports. 15 editors, ~150 authors total. Work from ~100 papers in 3 past years

Why Working on the Muon Collider

A **new interest** on muon colliders, **not** a **renewed** one

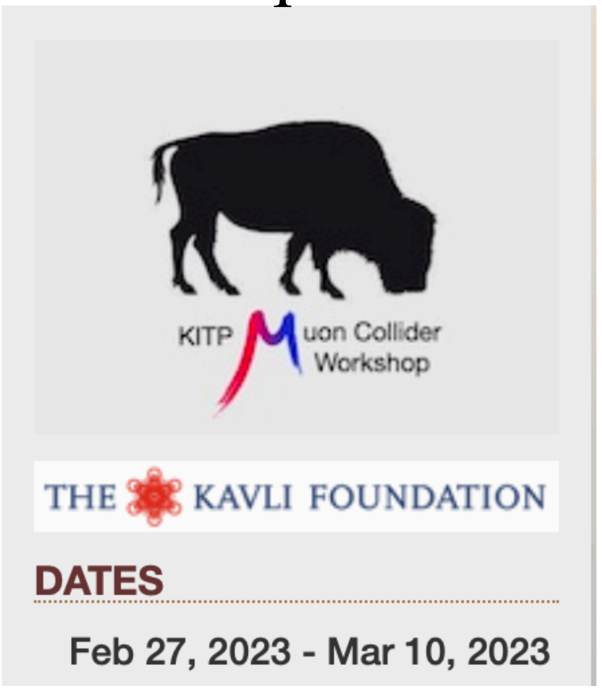


MuC WG EU Strat. Report: 2019

"A 10-TeV scale muon collider with sufficient integrated luminosity provides an energy reach similar to that of a 100 TeV proton-proton collider. […] muon and hadron colliders have similar reach and can significantly constrain scenarios motivated by the naturalness principle. […] Multi-TeV muon colliders will have the benefit of excellent signal to background […] One of the key measurements from the multi-TeV colliders is the one of the Higgs self-coupling to a precision of a few percent, and the scanning of the Higgs potential."

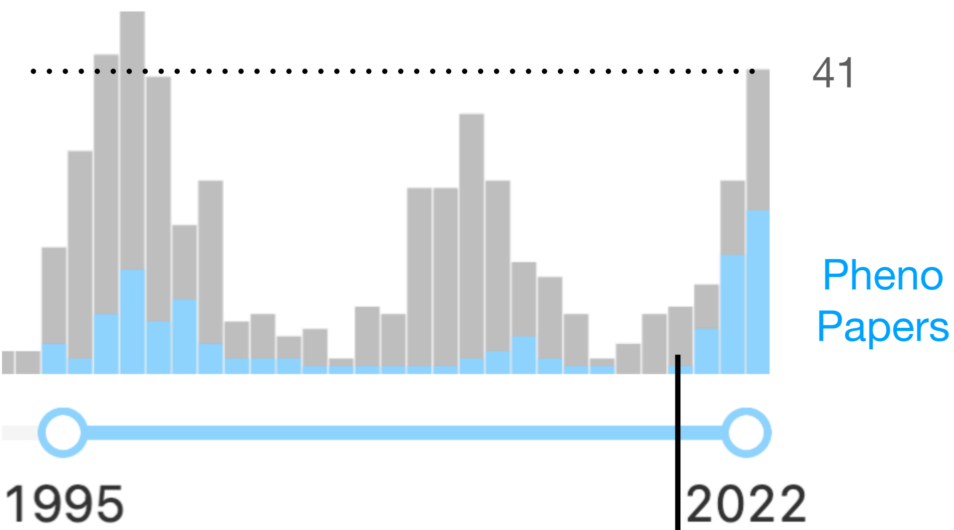
From Snowmass EF report. Based on 2 IMCC + 1 MuC Forum reports. 15 editors, ~150 authors total. Work from ~100 papers in 3 past years

Workshop at KITP:



Why Working on the Muon Collider

A **new interest** on muon colliders, **not** a **renewed** one

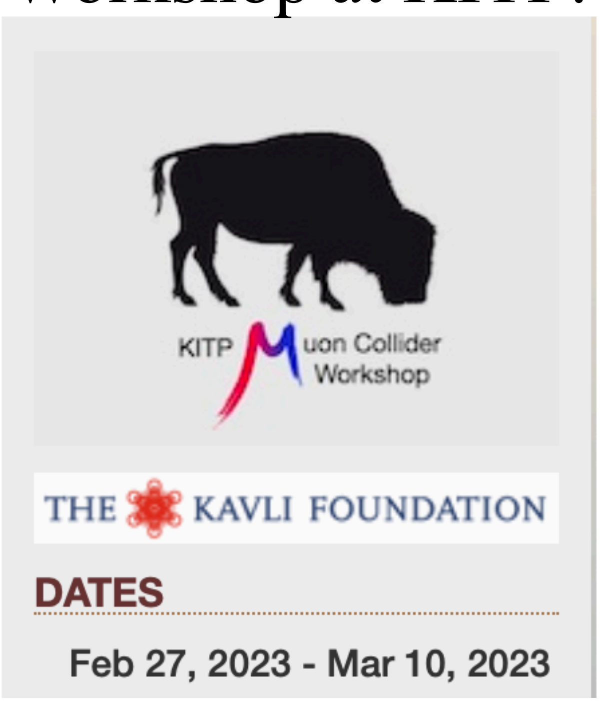


MuC WG EU Strat. Report: 2019

”A 10-TeV scale muon collider with sufficient integrated luminosity provides an energy reach similar to that of a 100 TeV proton-proton collider. […] muon and hadron colliders have similar reach and can significantly constrain scenarios motivated by the naturalness principle. […] Multi-TeV muon colliders will have the benefit of excellent signal to background […] One of the key measurements from the multi-TeV colliders is the one of the Higgs self-coupling to a precision of a few percent, and the scanning of the Higgs potential.”

From Snowmass EF report. Based on 2 IMCC + 1 MuC Forum reports. 15 editors, ~150 authors total. Work from ~100 papers in 3 past years

Workshop at KITP:



An enthusiastic community:

Why Working on the Muon Collider

Why this enthusiasm?

1. Before LHC, thinking about other future colliders was less urgent
2. After LHC, need of perspective for ambitious jump ahead in energy exploration. Studies for F.C. such as FCC and CLIC prepared the ground.
3. We sharply identified 10+TeV as the final goal. Shorter-term physics opportunities are intermediate steps towards 10+TeV realisation.
4. MuC is very new! Both from Facility and from Physics point of view. People like working on MuC, because there is interesting work to do!

Why Working on the Muon Collider

Why this enthusiasm?

1. Before LHC, thinking about other future colliders was less urgent
2. After LHC, need of perspective for ambitious jump ahead in energy exploration. Studies for F.C. such as FCC and CLIC prepared the ground.
3. We sharply identified 10+TeV as the final goal. Shorter-term physics opportunities are intermediate steps towards 10+TeV realisation.
4. MuC is very new! Both from Facility and from Physics point of view. People like working on MuC, because there is interesting work to do!

Why Working on the Muon Collider

Why this enthusiasm?

1. Before LHC, thinking about other future colliders was less urgent
2. After LHC, need of perspective for ambitious jump ahead in energy exploration. Studies for F.C. such as FCC and CLIC prepared the ground.
3. We sharply identified 10+TeV as the final goal. Shorter-term physics opportunities are intermediate steps towards 10+TeV realisation.
4. MuC is very new! Both from Facility and from Physics point of view. People like working on MuC, because there is interesting work to do!

Furthermore:

MuC design and technology advances during and after MAP.
E.g., MICE demonstrated cooling; MUCOOL demonstrated RF in high B-field; 30 T magnets for final cooling demonstrated.

MuC now part of European Roadmap for Accelerator R&D.

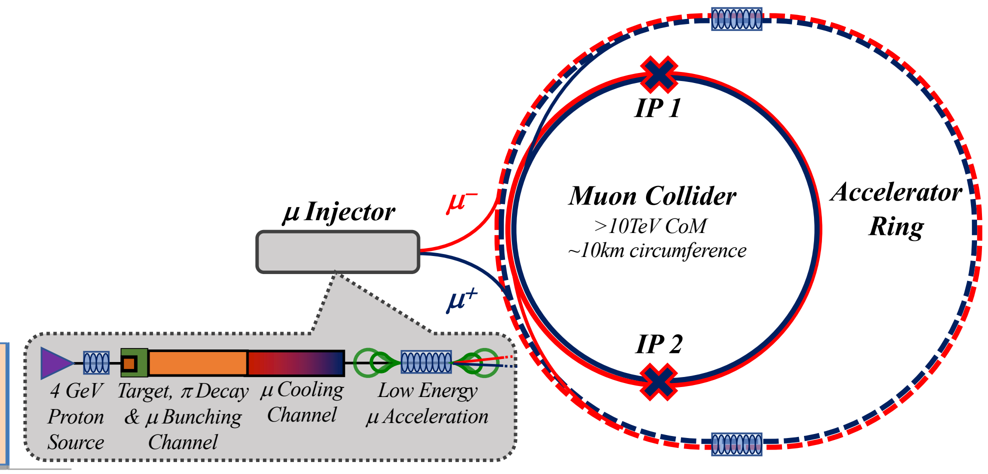
The **IMCC** started working full steam with more ambitious goal than MAP

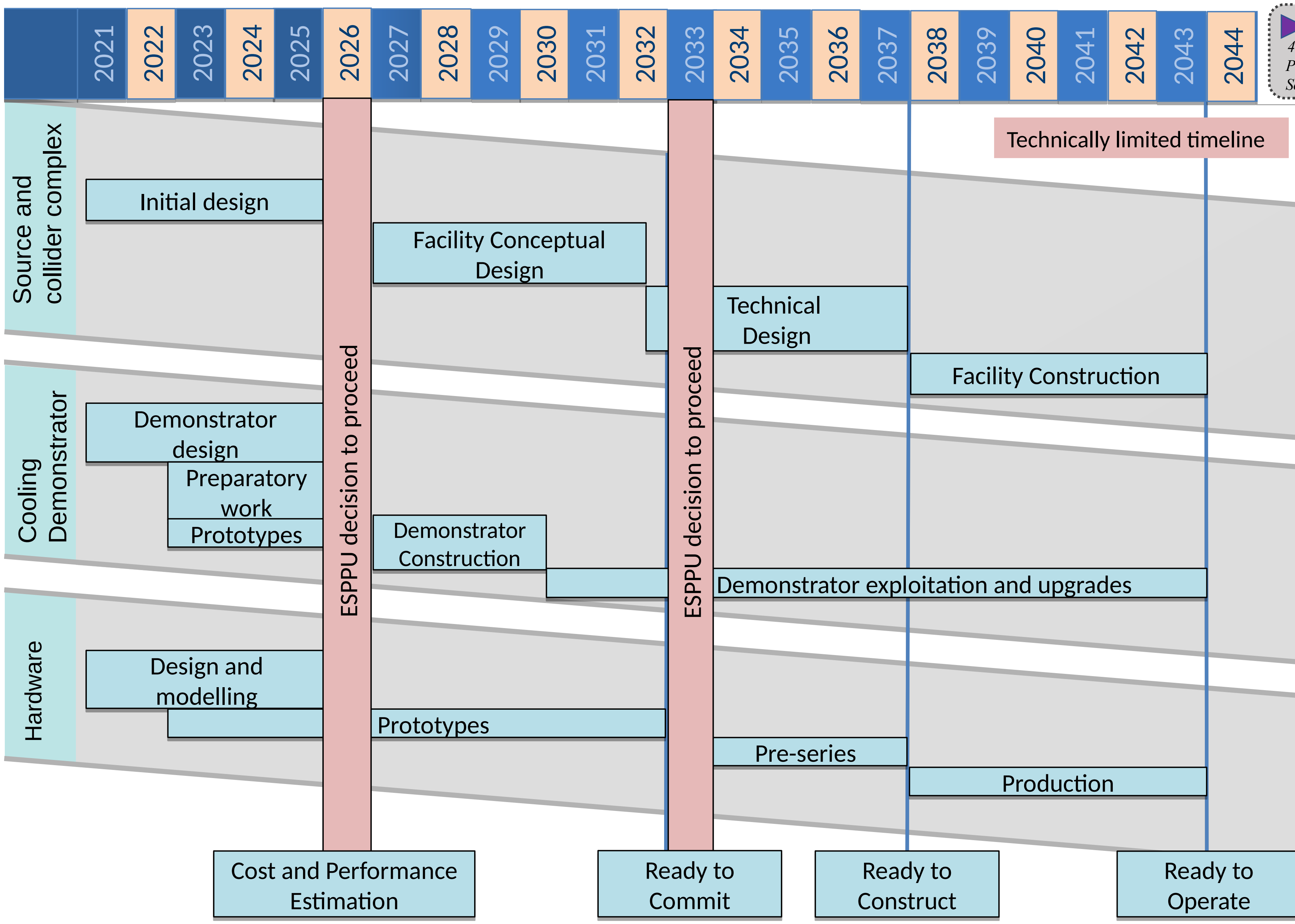
No showstopper identified. **Timeline** for R&D being implemented by IMCC

Muon Collider Plans

Technically limited timeline:

Soon we will know if concept mature for full CDR.
Demonstrator program will initiate right after.
Stay tuned for consolidated timeline release



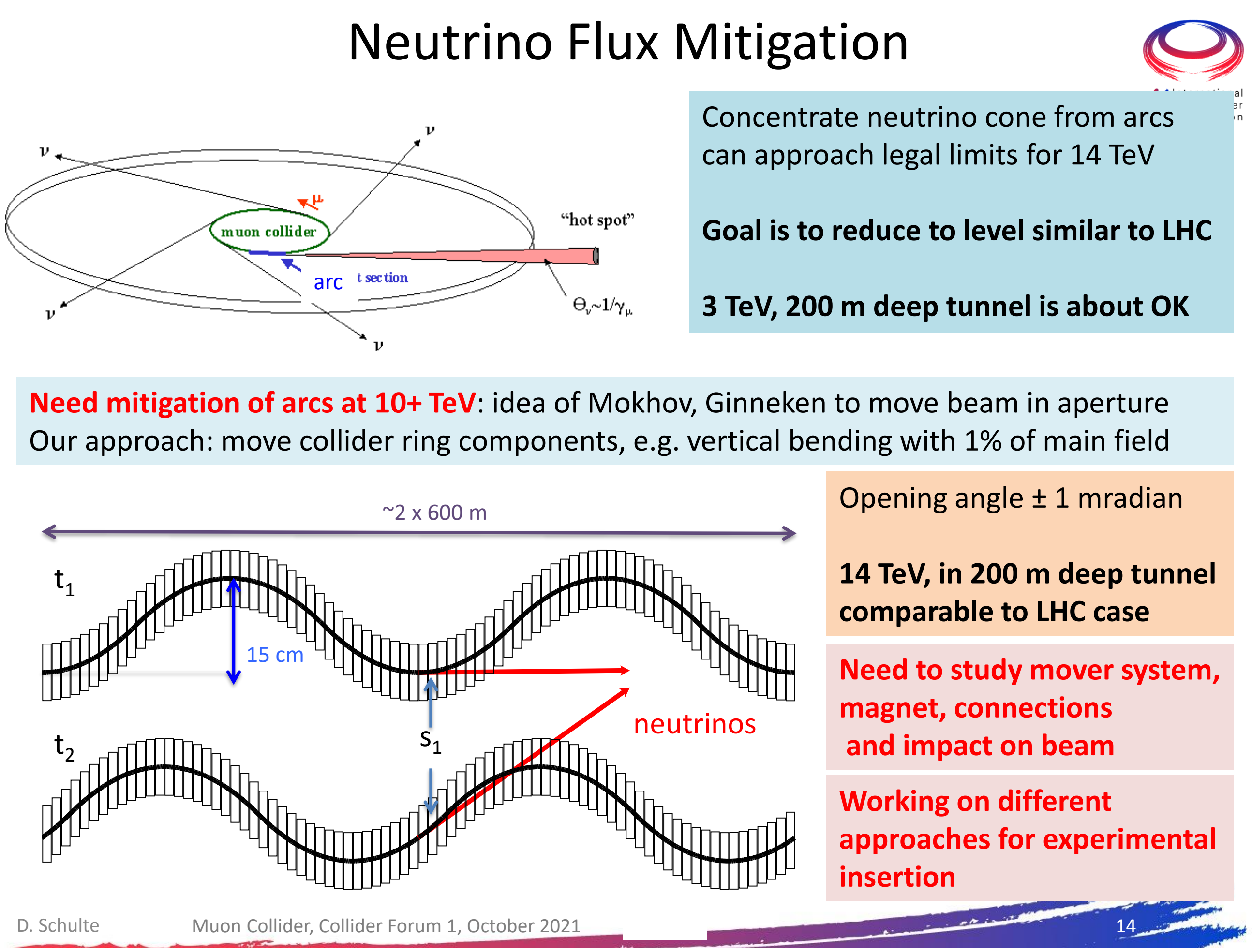


International MUON Collider Collaboration

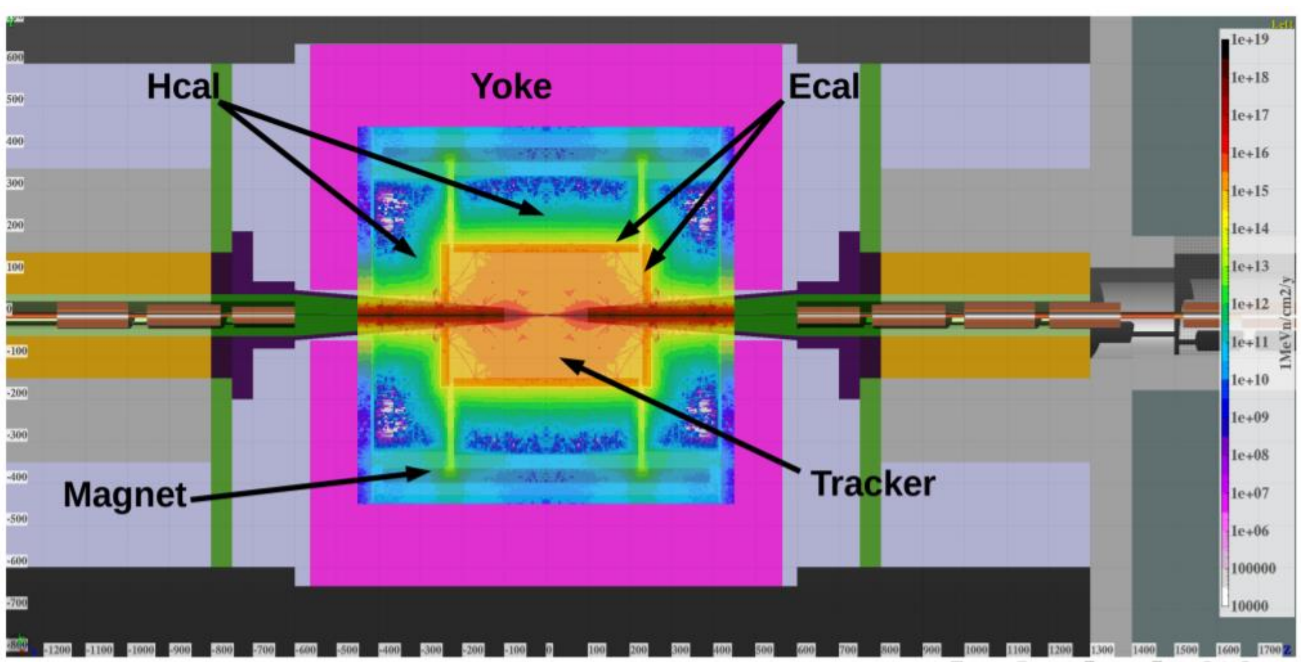
Muon Collider Plans

Principal Challenges:

Demonstrate neutrino flux mitigation system
Full design of collider and acceleration
Integration of muon production and cooling stages
Optimise collider/MDI for the suppression of BIB from muon decay

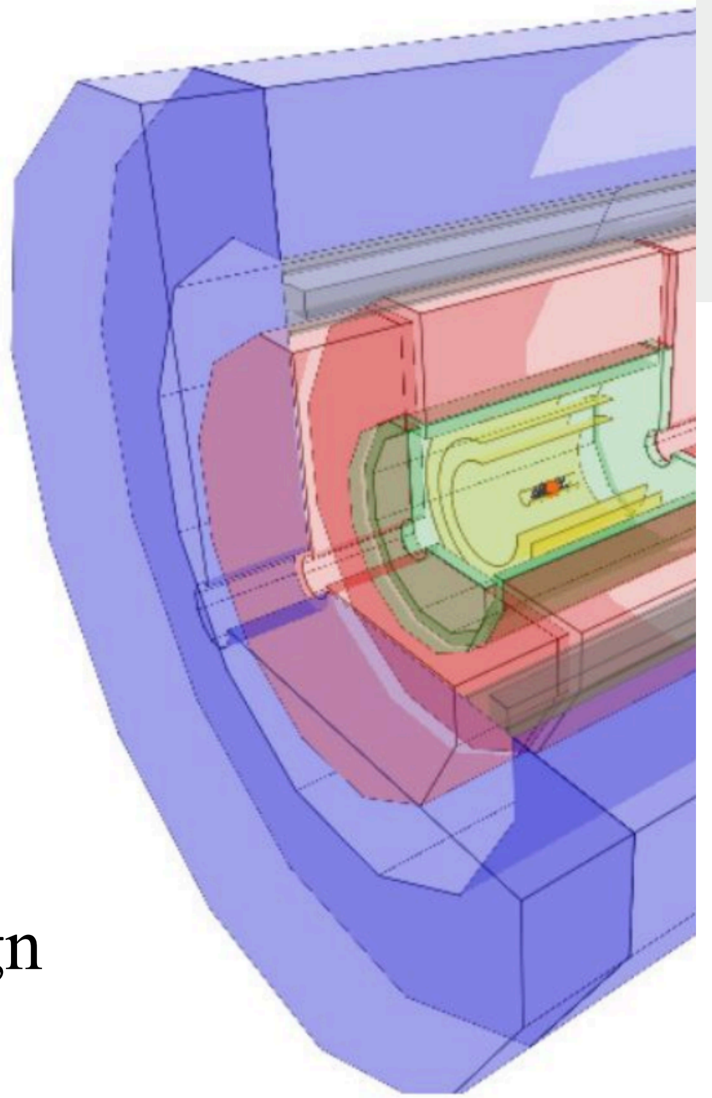


MuC features a novel type of BIB.
Detector and reconstruction design studies are crucial even at this early stage.



FLUKA @ 1.5 TeV

Experiment Design



Design detector for precision at multi-TeV scale

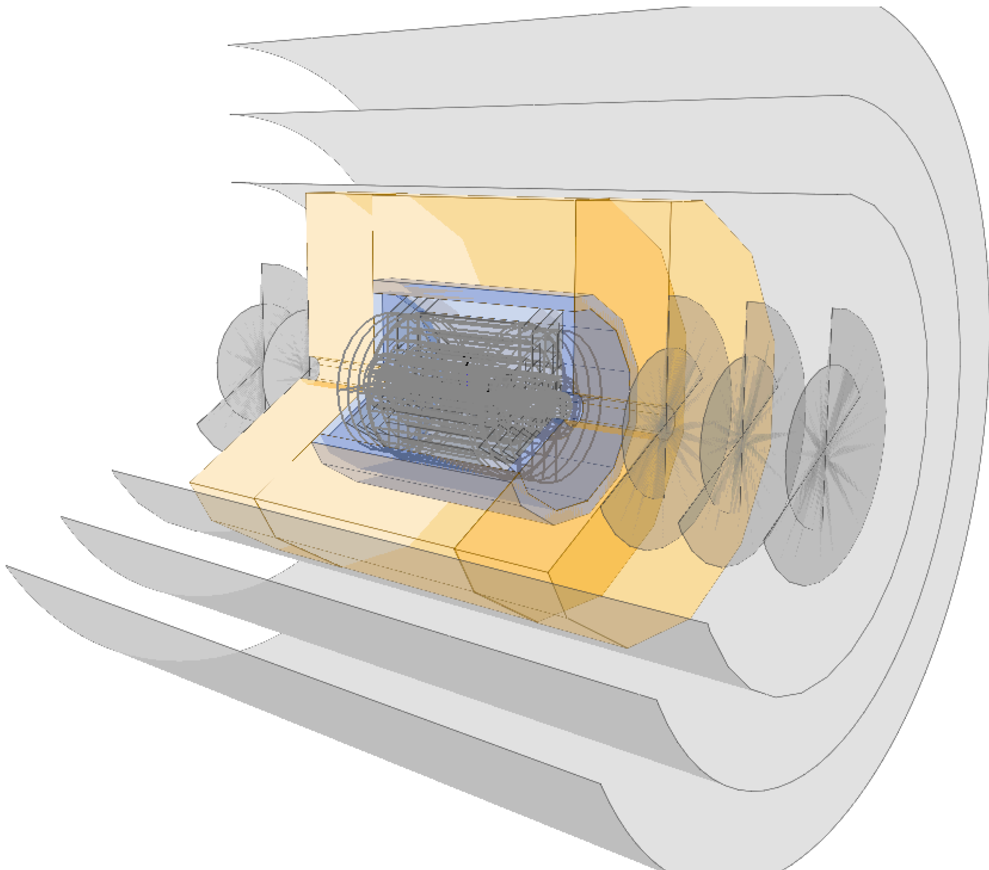
- Extract physics from GeV- and from TeV-energy particles
- Built-in sensitivity to “unconventional” signatures

The BIB is under control. See EPJC Review

- Demonstrated LHC-level performances with CLIC-like design
- Sensitivity to Higgs production
- Disappearing tracks detection

Exciting opportunities ahead

- Explore new detector concepts
- Identify and pursue key R&D requirements for technology development in next 20 years
- New challenges → new techniques that could be ported back to HL-LHC and F.C.
- Tackle the gigantic physics program of the MuC!



Conclusions

MuC could be best option for continuation of the HEP journey

R&D has initiated. Design consolidation will be soon completed.

Why working on muon collider physics?

It is **Important:** we must **consolidate** the potential, define **new targets**, **motivate** and **inform** Accelerator design.

It is **Fun:** novel BSM possibilities wait to be explored, as well as novel challenges for predictions, object reconstruction, BIB mitigation, etc.

The novelty of the theme and the lack of established solution enables and require innovative research that will **advance particle physics today**, on top of paving the way toward a muon collider further in the future.

Conclusions

The Very High Energy Muon Collider is a Dream

Conclusions

The Very High Energy Muon Collider is a Dream

And, often, Dreams DO become Reality!

Conclusions

The Very High Energy Muon Collider is a Dream

And, often, Dreams DO become Reality!

Thank You !

Backup

Theory Challenges

EW theory is weakly coupled, but observables are not IR safe

$$E_{\text{cm}} \gg m_W$$

Large muon collider energy

Small IR cutoff scale

Scale separation entails enhancement of Radiation effect.

Like QCD ($E \gg \Lambda_{\text{QCD}}$) and QED ($E \gg m_\gamma = 0$), **but:**

EW symmetry is broken:

EW color is observable ($W \neq Z$).

KLN Theorem non-applicable.

(inclusive observables not safe)

→ **Practical need** of computing EW Radiation effects

Enhanced by $\log^{(2)} E^2/m_{\text{EW}}^2$

EW theory is Weakly-Coupled

The IR cutoff is physical

→ **First-Principle** predictions **must** be possible

For arbitrary multiplicity final state

Theory Challenges

EW theory is weakly coupled, but observables are not IR safe

$$E_{\rm cm} \gg m_W$$

Large muon collider energy

Small IR cutoff scale

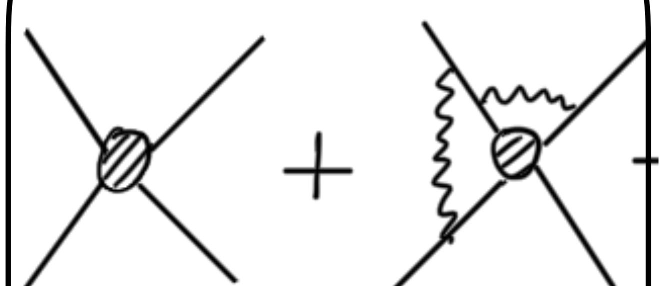
Scale separation entails enhancement of Radiation effect.

Quantitatively, resummation is needed.

10 TeV MuC

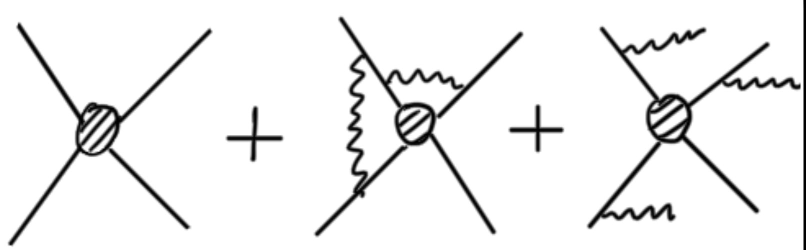
$$\exp\left[-g^2/16\pi^2 \log^2(E_{\rm cm}^2/m_{\rm w}^2)\times \text{Casimir}\right] \approx \exp[-1]$$

Exclusive X-S



Two hard bodies with **definite EW color**.
Veto on EW bosons.

Semi-Inclusive X-S



Two hard bodies of **definite EW color**.
EW bosons allowed.

Process	N (Ex)	N (S-I)
e^+e^-	6794	9088
$e\nu_e$	—	2305
$\mu^+\mu^-$	206402	254388
$\mu\nu_\mu$	—	93010
$\tau^+\tau^-$	6794	9088
$\tau\nu_\tau$	—	2305
jj (Nt)	19205	25725
jj (Ch)	—	5653
$c\bar{c}$	9656	12775
cj	—	5653

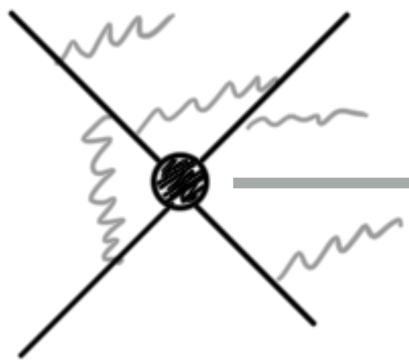
= charged

$b\bar{b}$	4573	6273
$t\bar{t}$	9771	11891
bt	—	5713
Z_0h	680	858
$W_0^+W_0^-$	1200	1456
$W_T^+W_T^-$	2775	5027
$W^\pm h$	—	506
$W_0^\pm Z_0$	—	399
$W_T^\pm Z_T$	—	2345

Theory Challenges

Benchmark predictions we must learn how to make:

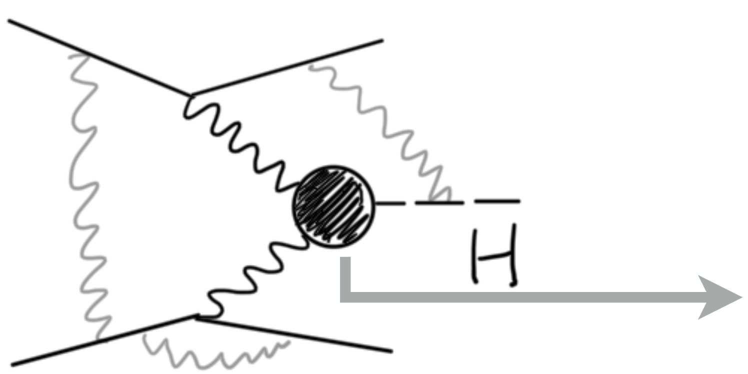
- Direct 2→2 annihilation:



$$\sqrt{\hat{s}} = E_{\text{cm}} \gg m_{\text{w}}$$

need X-S calculations and modelling of radiation (showering)

- EW-scale VBS: single Higgs production:



$$\sqrt{\hat{s}} = m_{\text{h}} \simeq m_{\text{w}}$$

same scale of radiation emission as of scattering